Injector systems: The ALBA Linac

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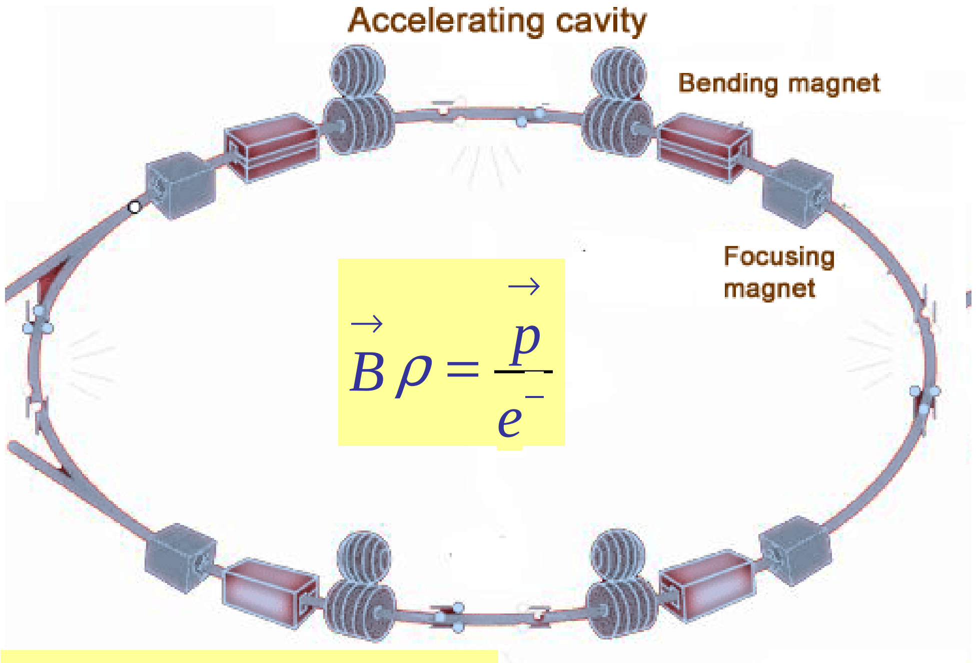
Outline

- Introduction to accelerators
- Injectors for high energy accelerators:
  - Linac
  - Cyclotron
  - Microtron
- Linac structure: the ALBA linac
- Electron sources for Linacs
- RF cavities
- Diagnostic
- Summary

Introduction

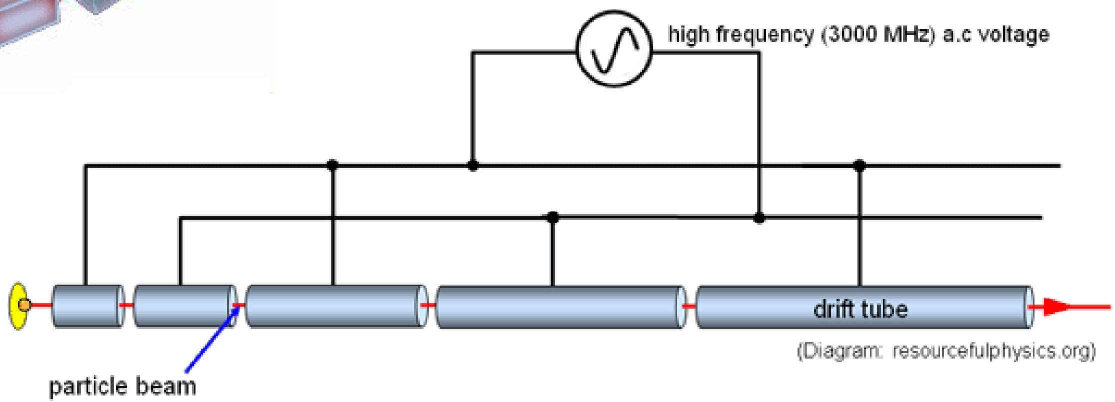
Accelerators: accelerate charged particles (e^-, e^+, p, ions,..)



$$\vec{B}\rho = \frac{\vec{p}}{e^-}$$

Circular Accelerator (synchrotron)

LINear ACcelerator



Introduction

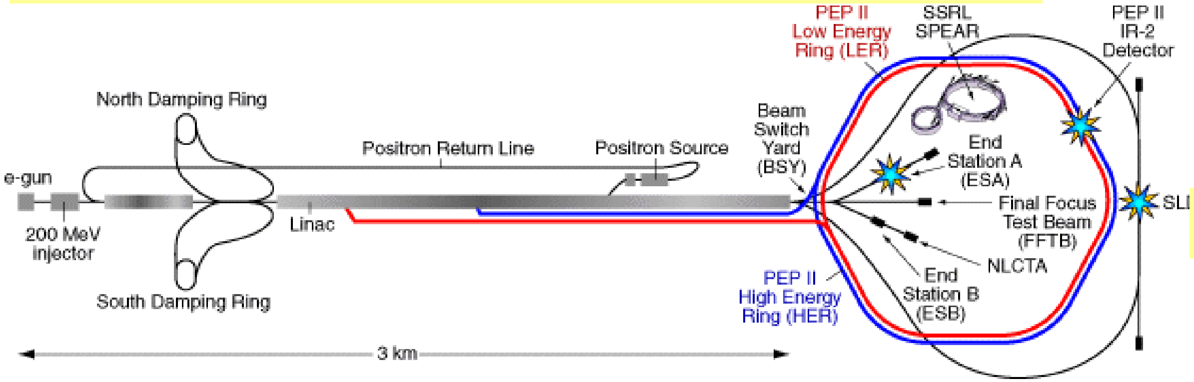
Circular	-Particles pass RF-cavities several times. -No space problem for RF-cavities. -Smaller in length than a Linac of comparable energy.
	-Particles loose energy by synchrotron radiation (especially low mass particles). Although in some cases it can be intended. -High magnetic fields are needed to turn high mass particles (protons)
Linear	-No energy loss due to synchrotron radiation. -High gradient: high energy gain in a short length. Handle high currents. -Well developed technology (industrial products)
	-Particles cross only once the RF-cavities. Low luminosity. -RF-cavities have to work at high frequencies (or small wavelengths) to reduce space.

- **Circular/Linear accelerator choice depends on:**

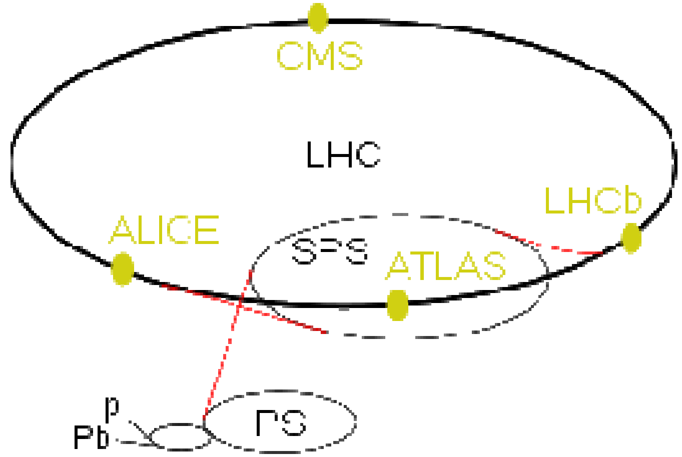
  energy range, costs, space reasons, type of particle, ...
- **In big projects, it is used a combination of both types.**

Examples

SLAC: 50 GeV Linac, 3.4 km, e^-/e^+ collisions



LHC: 7 TeV, 27 km, p / $\bar{p}$ collisions



100 times bigger! Need 300 km Linac

Next big projects with electron / positron LINAC colliders:

CLIC: 3 TeV, superconducting @ 12 GHz, 100 MV/m gradient, 2 linacs, total length: 48 km!

ILC: 500 GeV, 31 MV/m, superconducting, 2 linacs, total length: 31 km!

Injectors

•Synchrotrons can not accelerate particles from a starting energy E_i=0.

•Magnets that can produce a linear and homogeneous magnetic field starting from low current do not exist.

•Synchrotrons accelerate particles from energies about E_i~20 MeV.

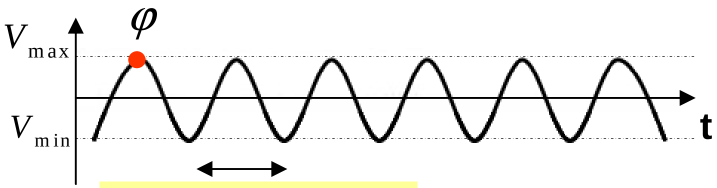
Typical injectors for synchrotron are:

- Linac
- Microtron:
- Cyclotron

Injector: Linac

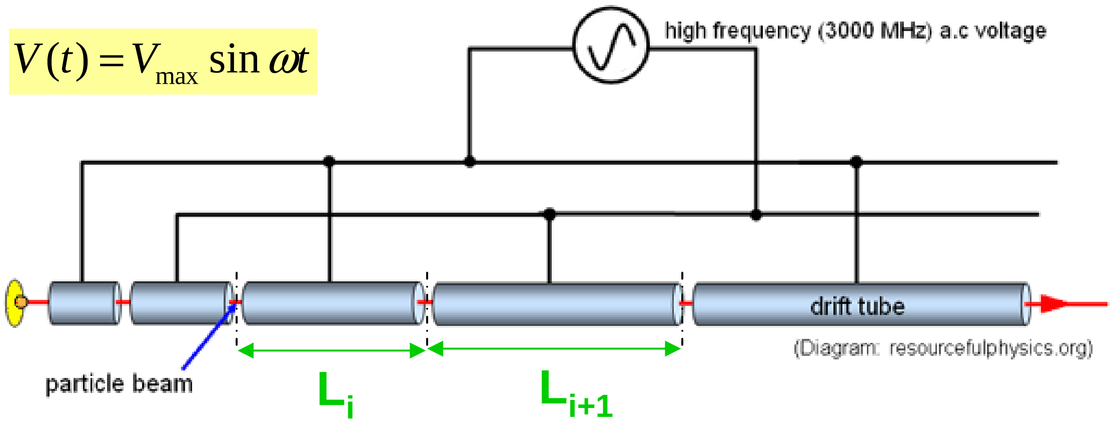
The particle acceleration using electrostatic voltage is technically limited to hundreds of kV due to discharges.

Solution: Use of an alternating voltage of the form (usually high frequency RF):



$$\lambda = \frac{c}{\nu_{RF}} = c\tau_{RF}$$

$$V(t) = V_{\max} \sin \omega t$$



- Particles "see" only the positive voltage.
- Drift tubes shield negative voltages.
- RF voltage moves $\tau_{RF}/2$ while particle travels through one drift section.
- RF frequency is constant.
- Particles velocity v_i increase.

Required separation between gaps i and i+1:

$$L_i = \frac{v_i \tau_{RF}}{2} = \beta_i \frac{\lambda_{RF}}{2}$$

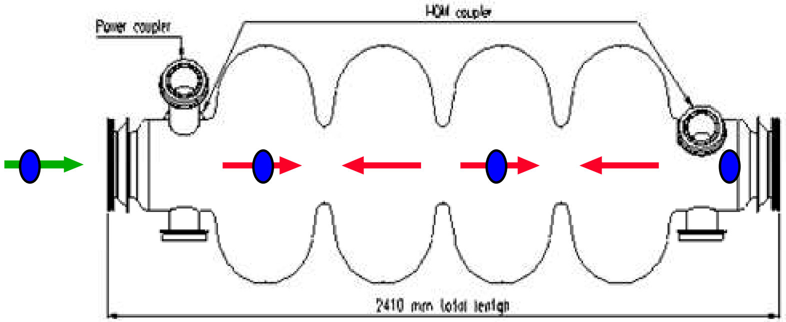
Energy reached after the i-drift tube:

$$E_i = iqV_{\max} \sin \varphi$$

Injector: Linac

Instead of drift tubes we can also use RF-cavities

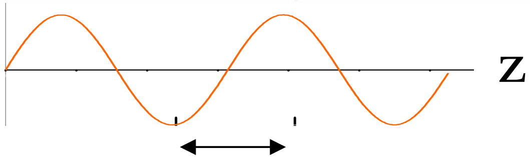
Beam



Synchronism condition bw. particle and wave

t (travel between centers of cells) = *T/2*

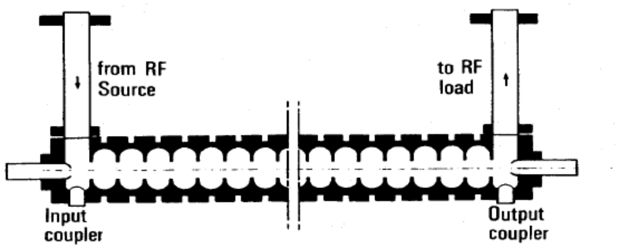
Electric field
(at time t_0)

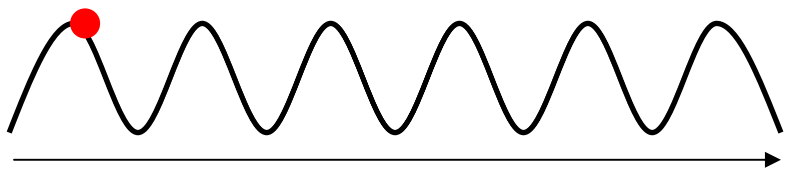


$$\frac{d}{\beta c} = \frac{1}{2f} \Rightarrow d = \frac{\beta c}{2f} = \frac{\beta\lambda}{2}$$

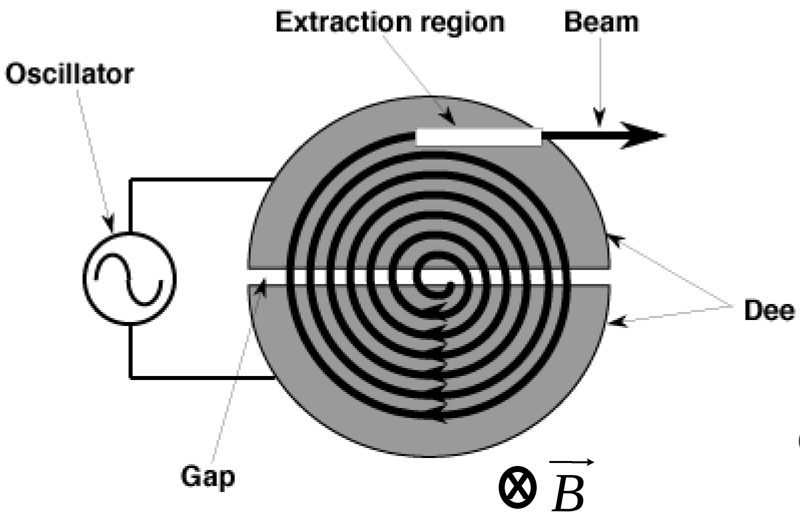
d=distance between centres of consecutive cells

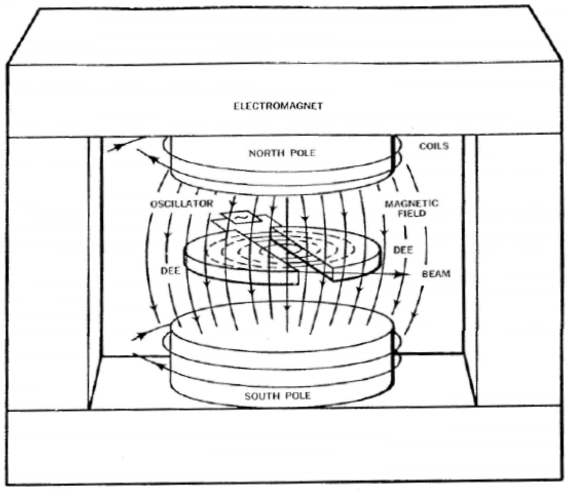
standing vs. traveling wave





Injector: Cyclotron





Ex.: Cyclotrons in PSI (Switzerland)
Up to 600 MeV protons (v = 0.6c)

Classical Cyclotron:

Use for non-relativistic particles (protons, ions, ...)

Cyclotron frequency: $\omega_{cyclotron} = \frac{e}{m} B$

Acceleration Condition: $\omega_{RF} = \omega_{cyclotron}$

Cyclotron frequency is not constant for relativistic particles:

$$\omega_{cyclotron} = \frac{e}{\gamma m} B$$

Then, $\omega_{RF} > \omega_{cyclotron}$

NO acceleration!!

SynchroCyclotron:

RF is decreased to accomplish the condition $\omega_{RF} = \omega_{cyclotron}$

Beam intensity is reduced, less bunches.

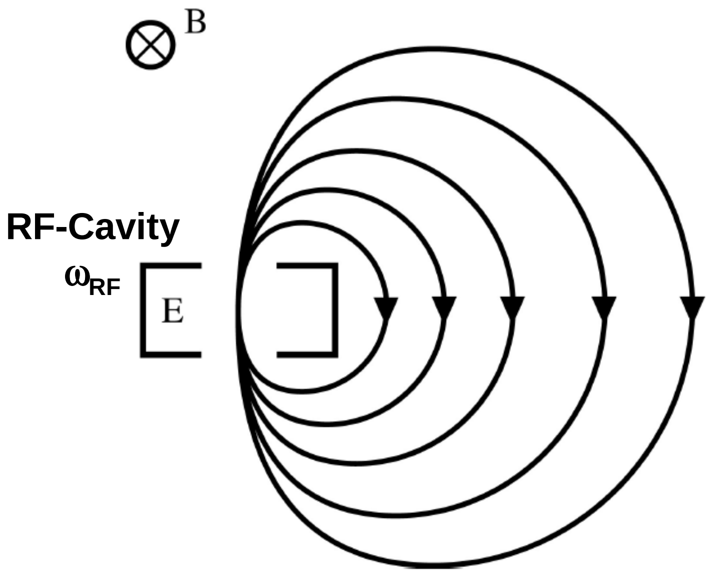
IsoCyclotron:

B is increased to keep the cyclotron fequency constant.
More effective type.

Injector: Microtron

- Mainly used to accelerate electrons and positrons.
- At low energy, they are a good alternative to Linacs.

Classical microtron:



- B = constant. Size magnet limits energy.
- Not necessary $\omega_{revolution}$ be constant.
- Condition: particles have to “see” the same RF phase. Therefore, for one turn:

$$\Delta t = \frac{k}{\nu_{RF}}$$ K: integer

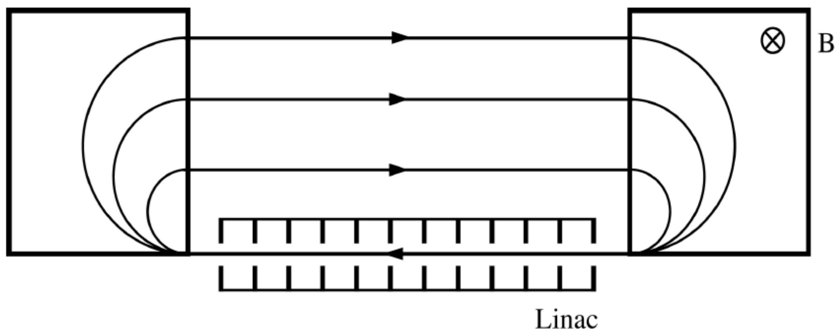
$$\Delta t = \frac{2\pi}{ec^2 B}\Delta E$$

Δt:time needed for one turn, ΔE: energy gained in one turn

- Energy range: typically 25-30 MeV, 3 GHz

Race-track microtron:

- Improve energy gain
- Up to 855 MeV (Mainz Microtron)



ALBA Synchrotron Light Facility

LINAC

Linacs are mainly used in:

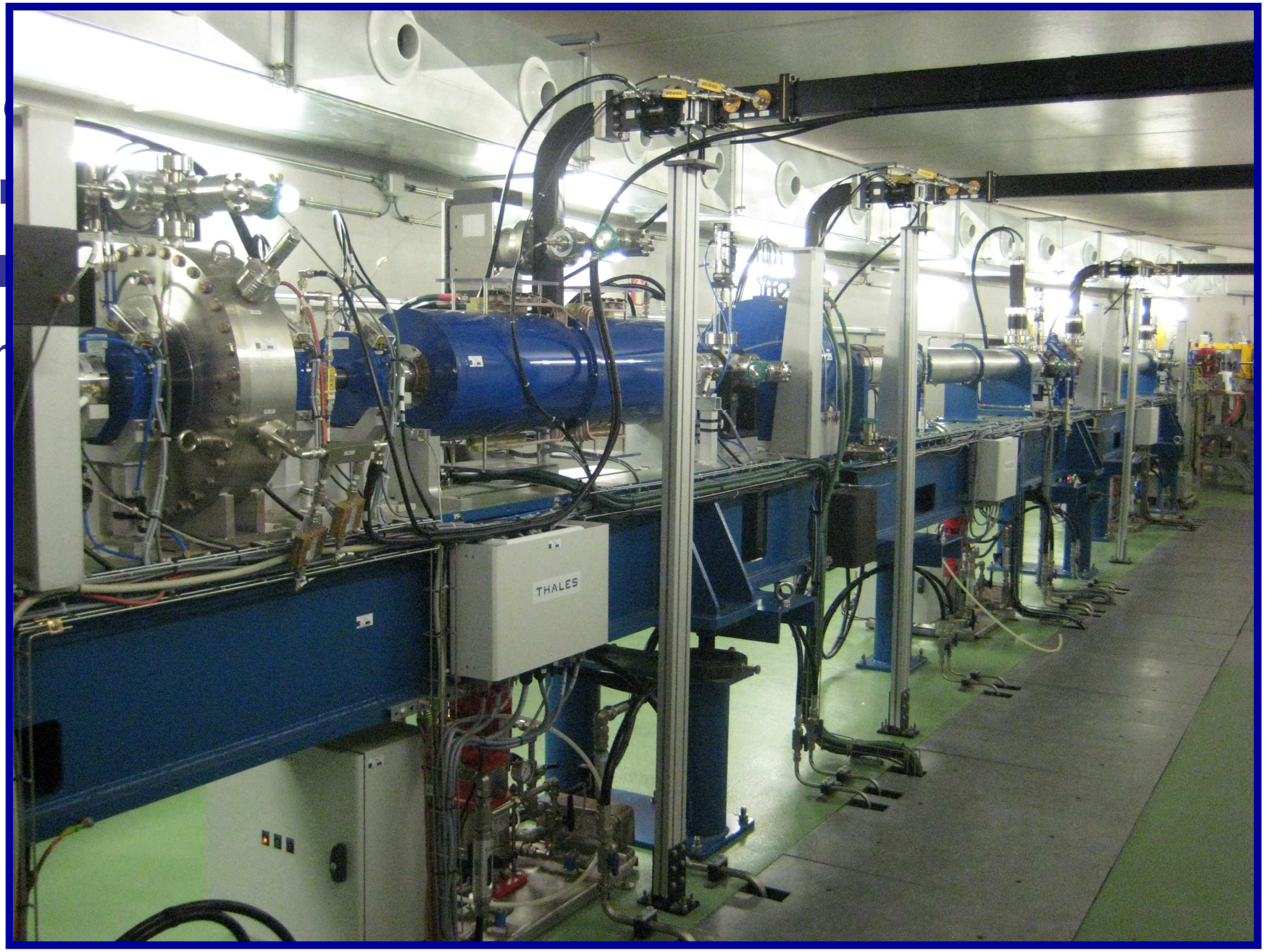
-Industry (X-ray tubes)

-Medical treatment (Can

-Production of high ene

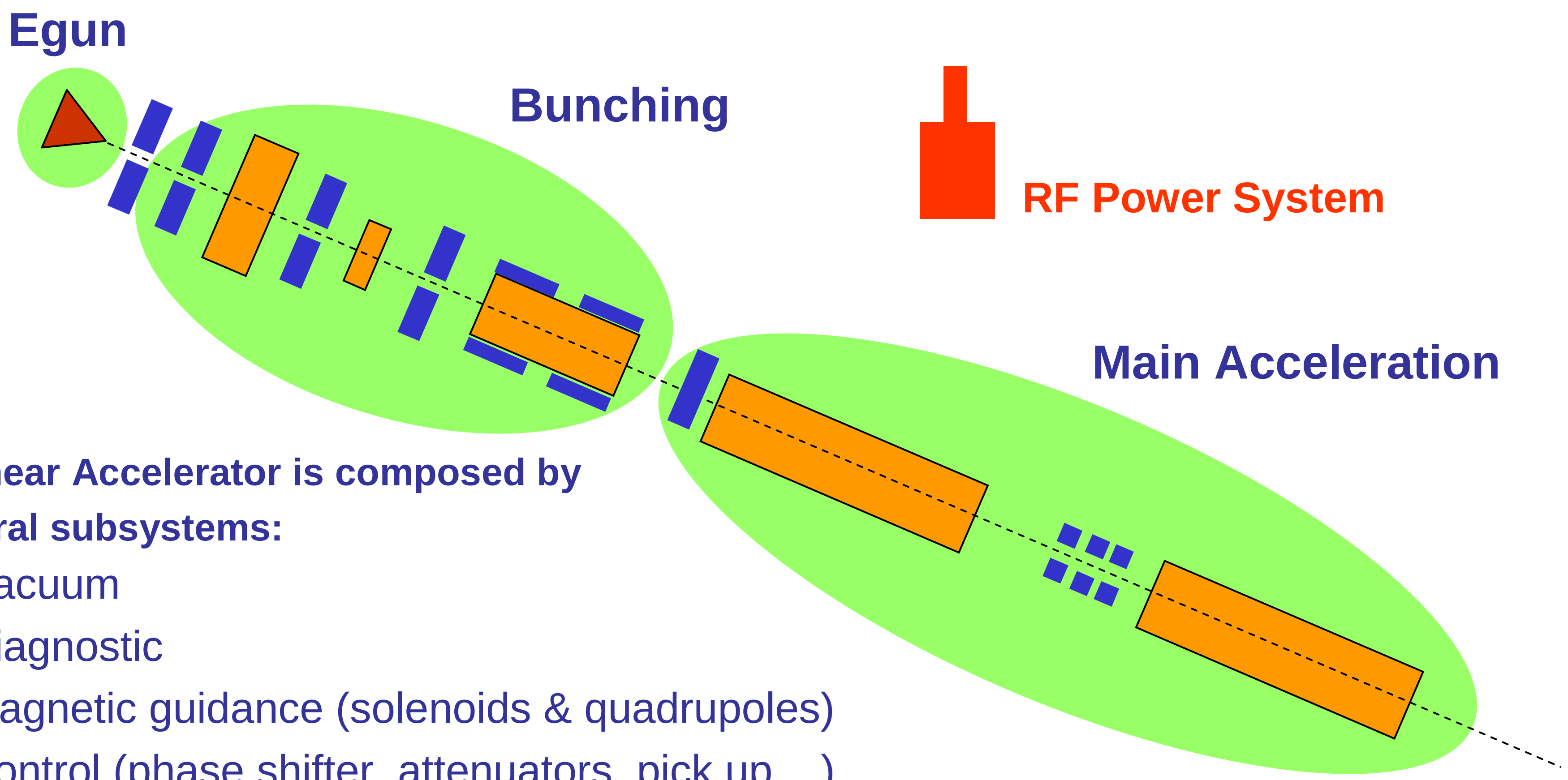
-Linear Collider (SLAC, I

-Injector for synchrotron



The ALBA Linac

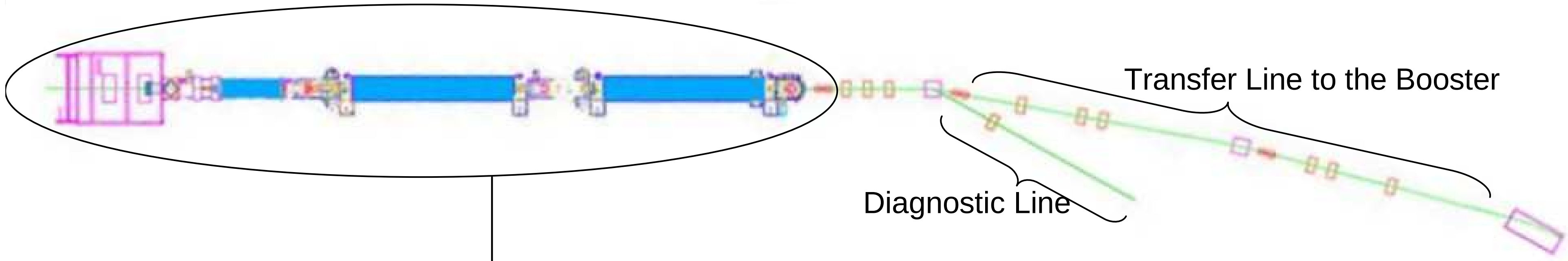
Linac main elements

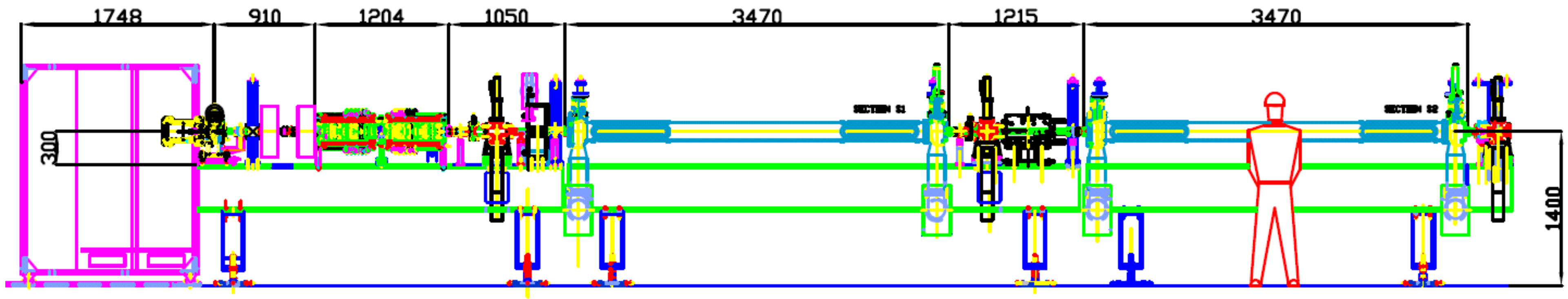


A Linear Accelerator is composed by several subsystems:

- -Vacuum
- -Diagnostic
- -Magnetic guidance (solenoids & quadrupoles)
- -Control (phase shifter, attenuators, pick up,...)
- -Cooling (temperature regulation water loops)
- -Timing
- -Power supply (e.g. Klystrons)
- -...

Linac complexity can vary within several orders of magnitude depending on energy, dimension, etc ...





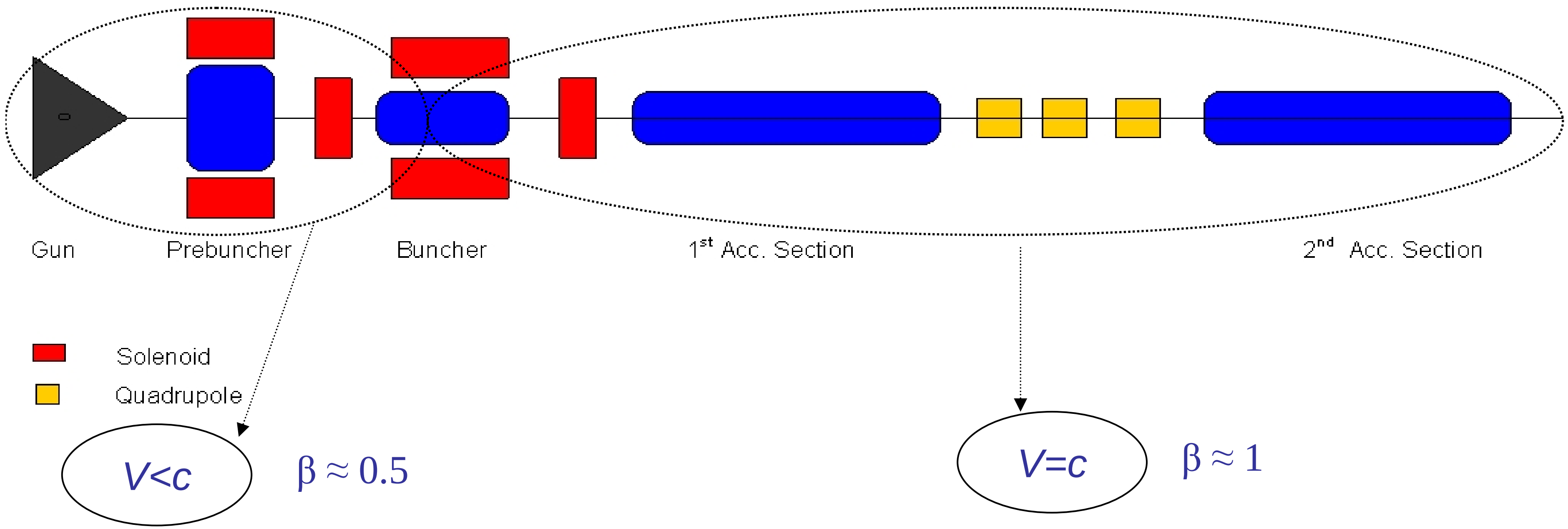
Electron gun
+
Power Supply

Bunching section
+
Solenoids

1st and 2nd accelerating sections
+
Triplet of quadrupoles in the middle

Total length ~ 13 m

Linac structure

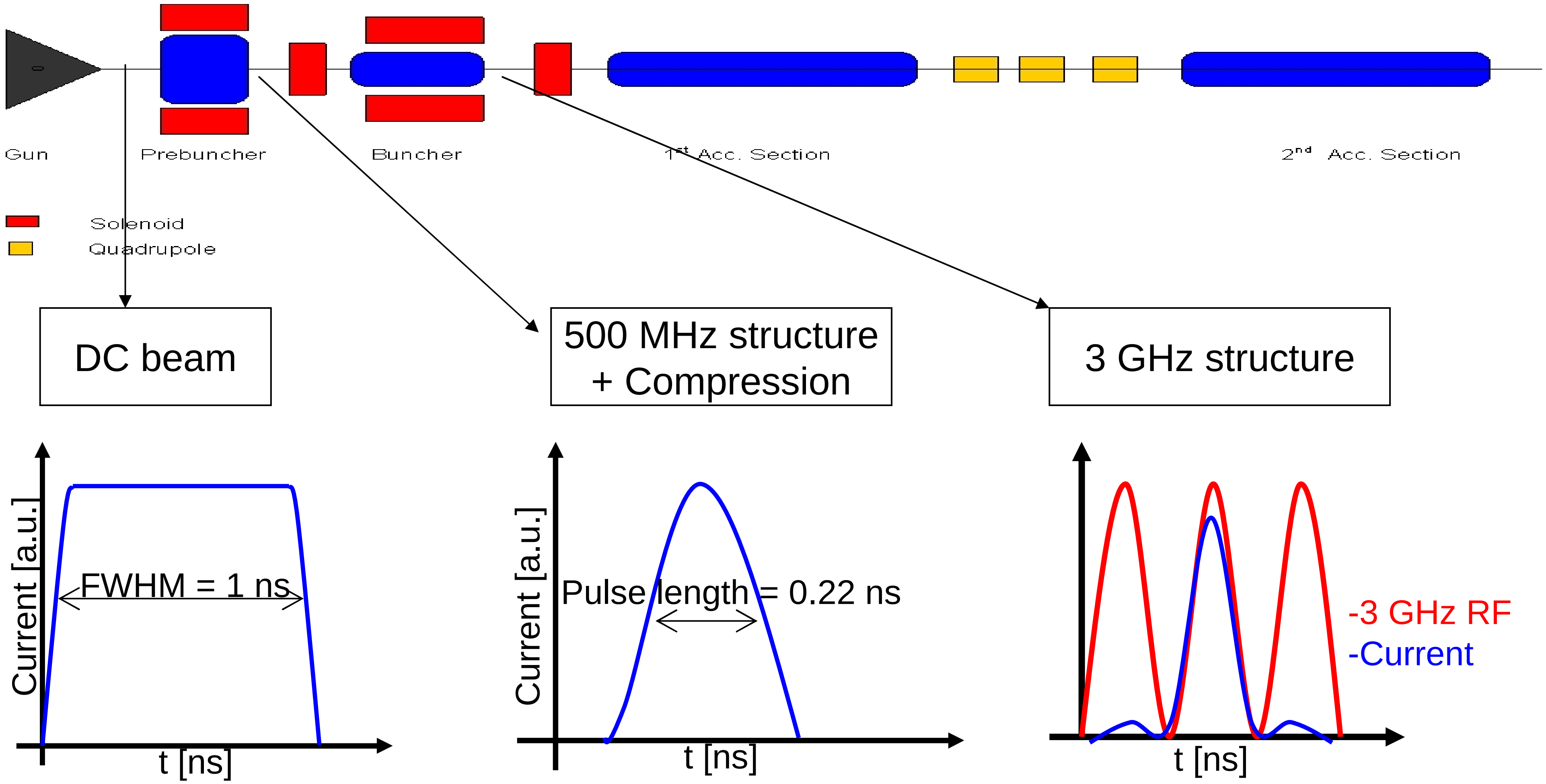


- Electron gun
- Bunching system

- Accelerating Sections

Along the linac there is magnetic guidance by solenoids and quadrupoles.

Linac structure

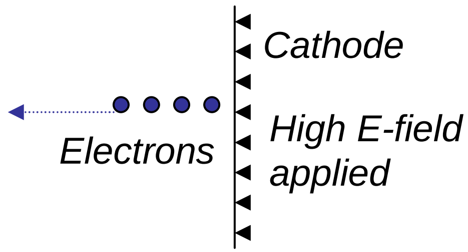


ALBA Synchrotron Light Facility

Electron sources

Electrons can be generated by different mechanisms

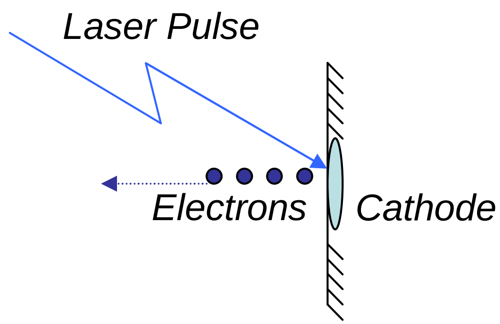
Field Emission Cathode



Fowler-Nordheim equation:

$$J = \frac{A}{\Phi}(\beta V)^2 \exp\left[-\frac{B\Phi^{3/2}}{\beta V}\right]$$

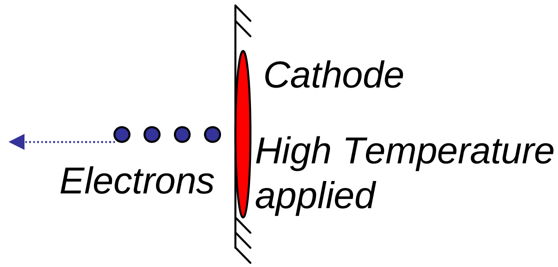
Photocathode



Number of emitted electrons:

$$N = 7.74\times10^{21}\cdot\frac{QE_{[\%]}\cdot W_{[J]}}{\lambda_{[nm]}}$$

Thermoionic cathode

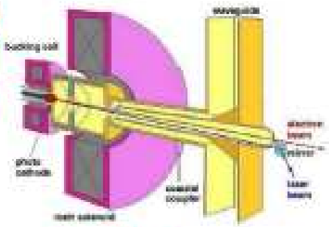


Richard-Duschmann equation:

$$J = AT^2 \exp\left[-\frac{e(\Phi_w - \Phi_{qt})}{K_B T}\right]$$

Photon electron RF guns

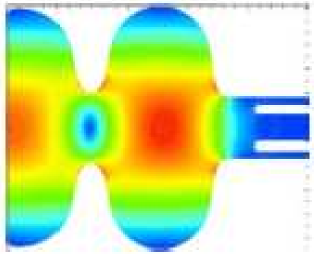
NCRF



pulsed!

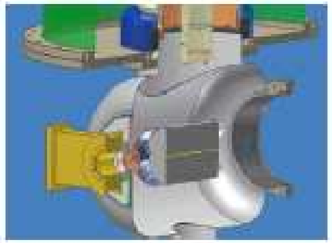
E_{cath} = 120 MV/m
τ_{laser} = 2.7 ps rms
σ_{laser} = 0.5 mm rms

SRF



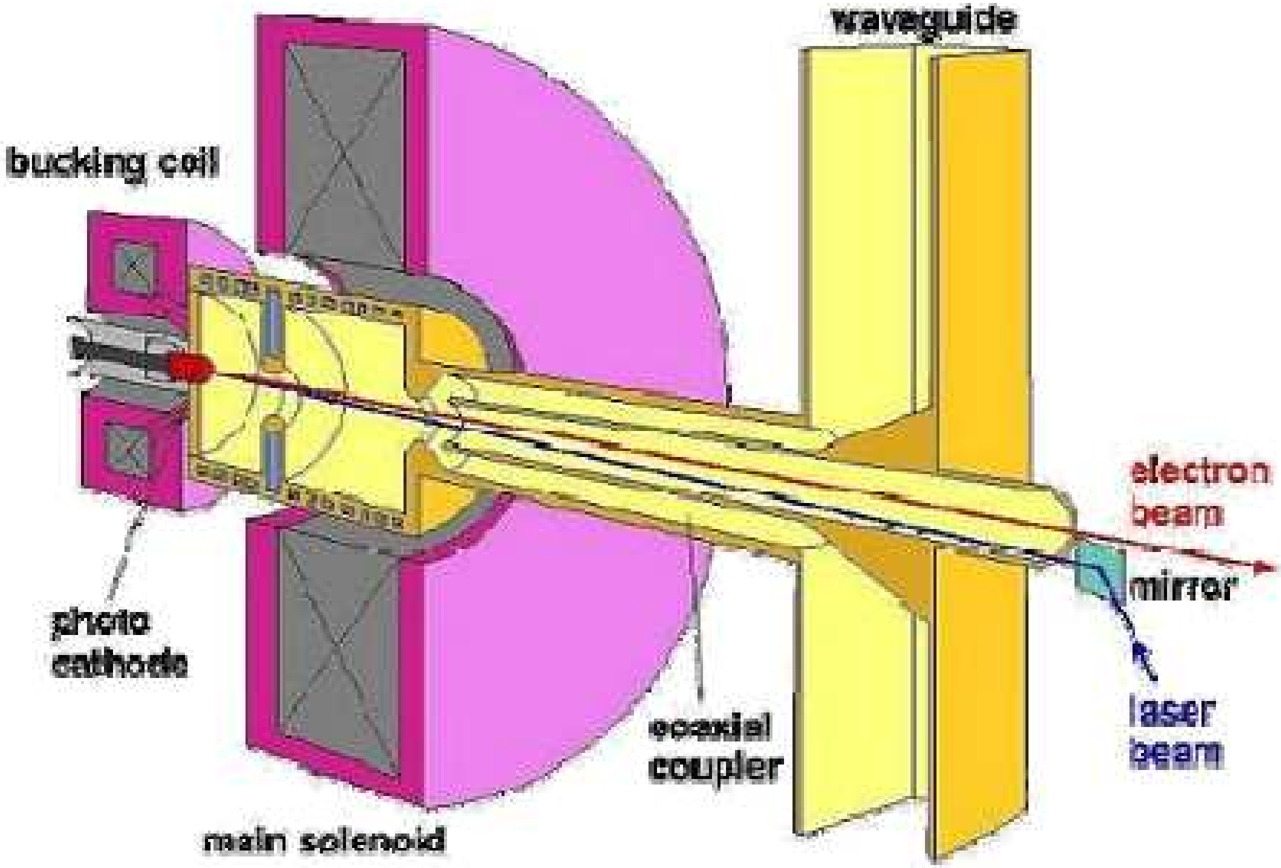
E_{cath} = 43 MV/m
τ_{laser} = 5.8 ps rms
σ_{laser} = 0.85 mm rms

DC



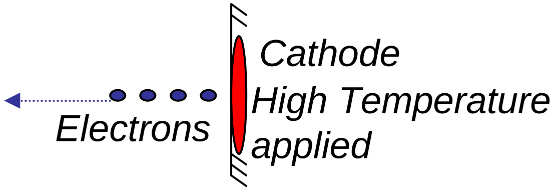
E_{cath} = 8 MV/m
τ_{laser} = 13 ps rms
σ_{laser} = 2 mm rms

By Bruce Dunham, Cornell


waveguide
bucking coil
electron
beam
mirror
photo
cathode
coaxial
coupler
laser
beam
main solenoid

Thermoionic electron gun

Thermoionic cathode

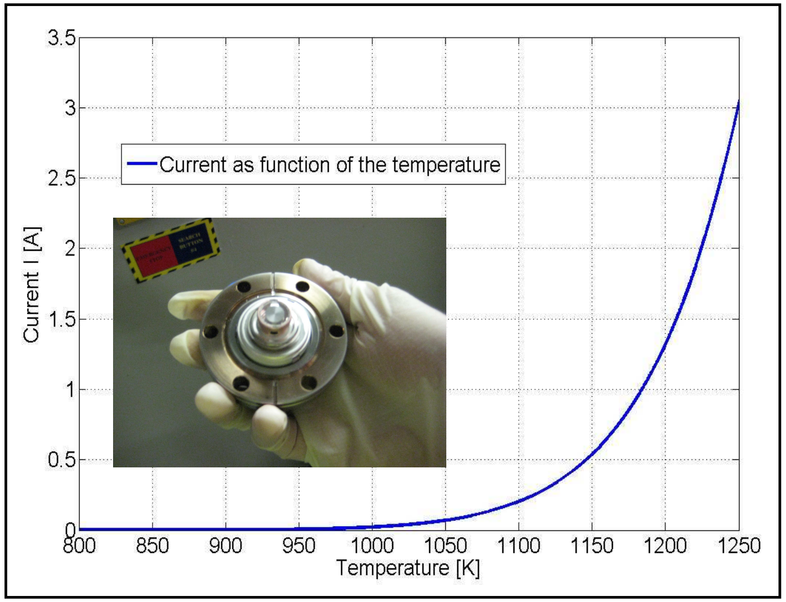


Richardson-Duschmann equation:

$$J = AT^2 \exp\left[-\frac{e(\Phi_w - \Phi_{qt})}{K_B T}\right]$$

ALBA Electron gun parameters:

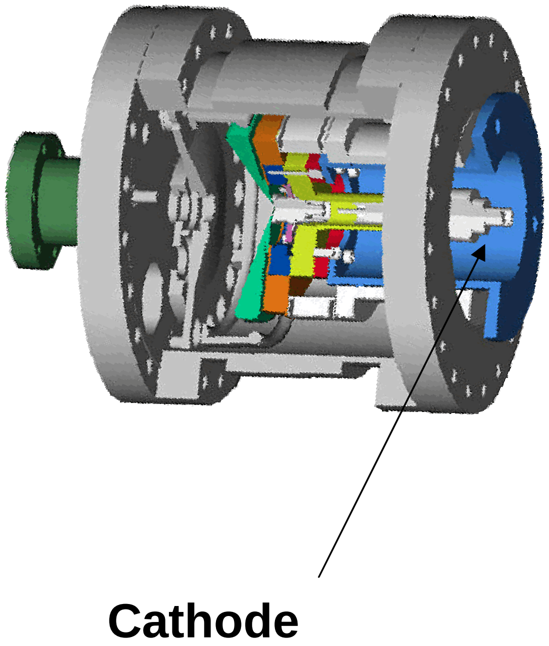
Cathode Area	0.5 cm^2	
Distance Cathode-Anode	30 mm	
Voltage	90 kV	
	Single Bunch	*Multi Bunch*
Beam Divergence	6 mrad	-9 mrad
Beam Radius	2.9 mm	1.8 mm

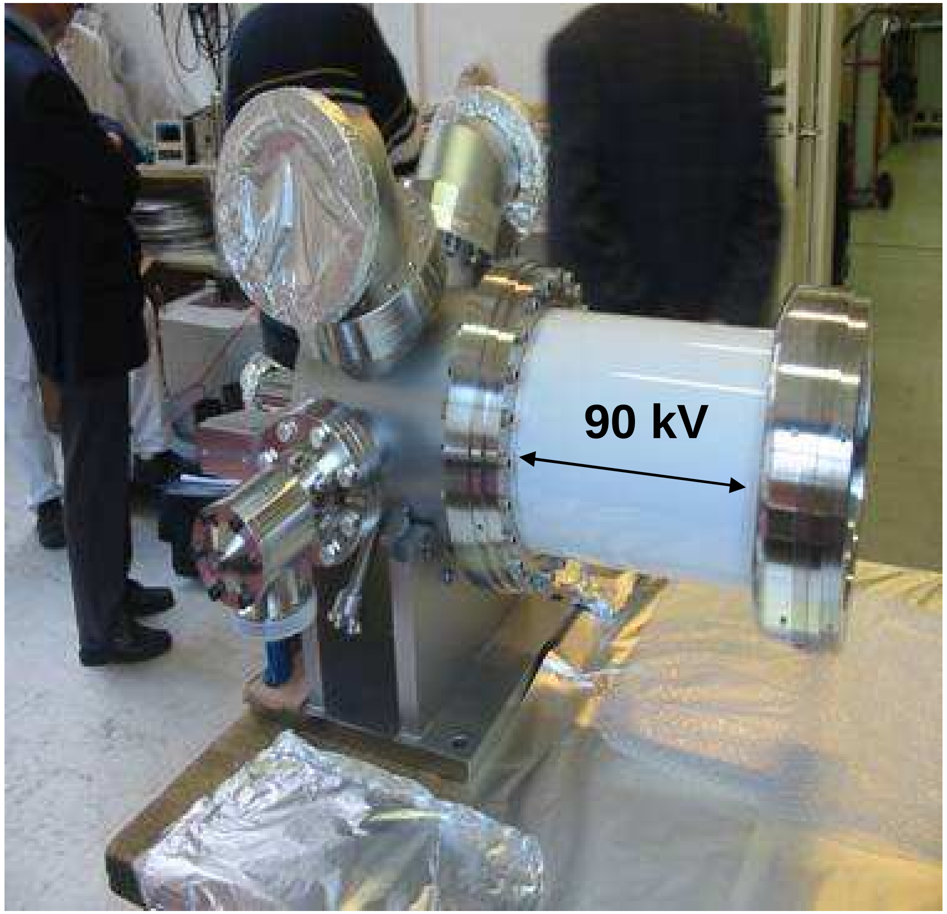


Minimum Emittance $\varepsilon_{thermoionic} = \sigma_x \sqrt{\frac{k_B T_0}{m_0 c^2}}$ $\Rightarrow$ $\epsilon_{thermoionic} = 10\ \pi$ mm mrad

Thermoionic cathodes are most used in electron linacs for synchrotron light sources (cheap, reliable, high current, well developed technology,...)

Thermoionic electron gun





Linac injection modes in ALBA

Single Bunch Mode (SBM)

Number of bunches per injection: 1-16

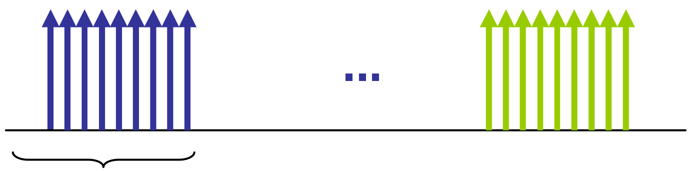
Time interval between bunches: 6-256 ns

Multi-Bunch Mode (MBM)

Number of bunches per injection: 18 - 512

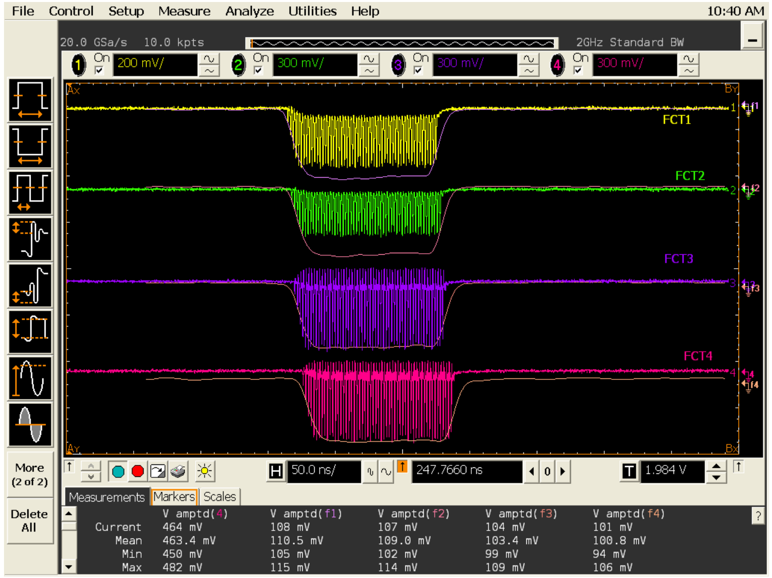
Time interval between bunches: fixed, 2 ns

Typical setting: 112 ns width pulse (56 bunches)



18 - 512 bunches

36 - 1024 ns



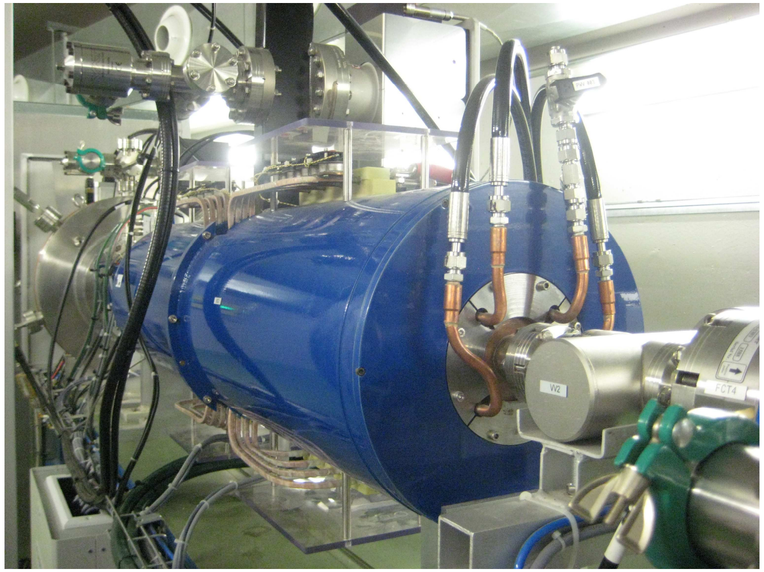
The bunching system

-Compresses the pulse in the longitudinal phase space

-Increases the energy up to some MeV (relativistic beam)

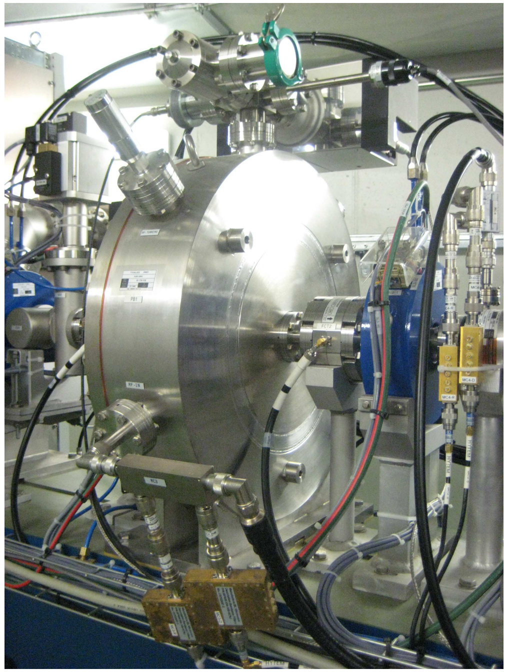
-In Alba consists of:

- -1 single cell cavity at 500 MHz
- -1 single cell cavity at 3 Ghz
- -1 standing wave buncher, 22 cell cavities, 3 GHz



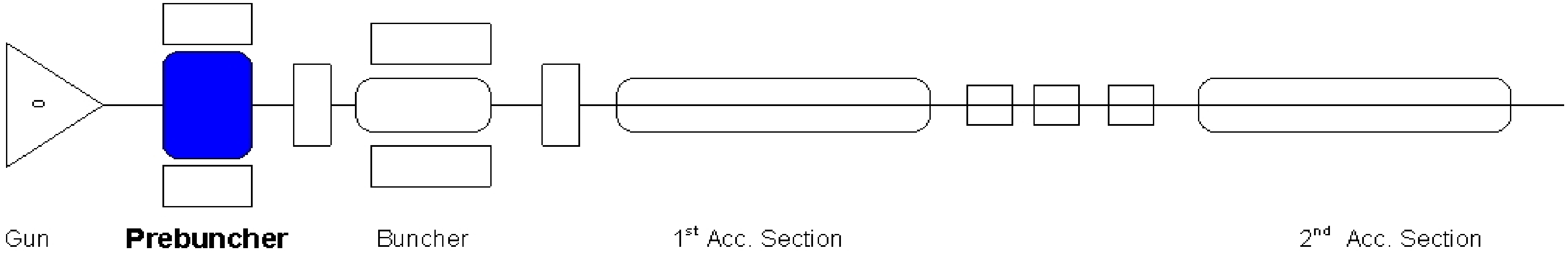
3 GHz

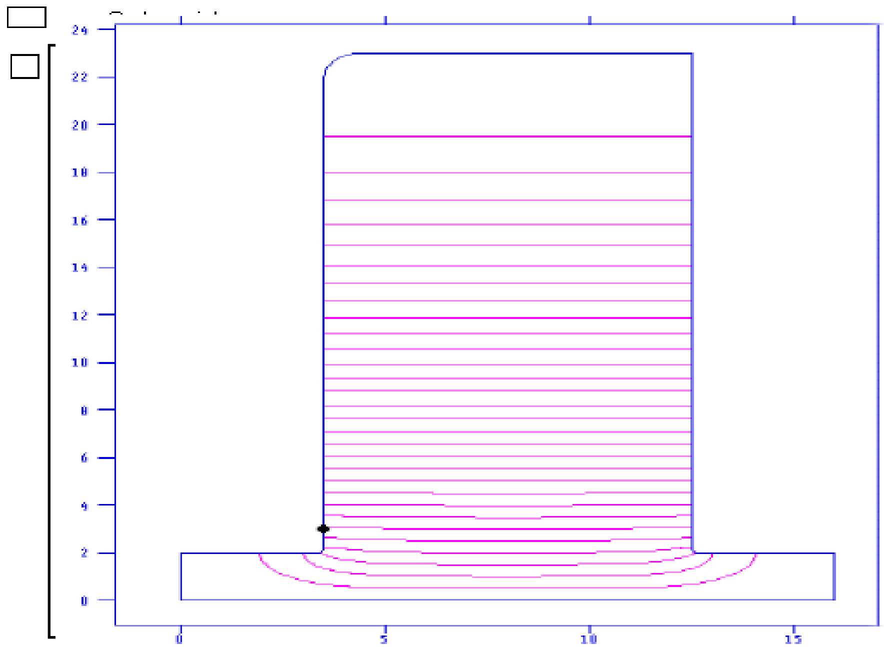
500 MHz



Sub-harmonic Pre-buncher

Single Cell Cavity working @ 500MHz (fundamental mode)





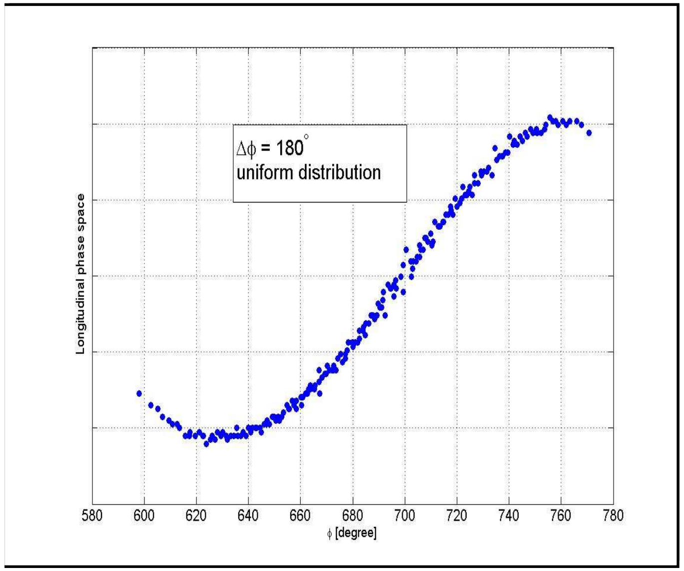
Freq.	499.654MHz
No. Cells	1
Total Length	30 cm
Q-Factor	21400
Shunt Impedance	29 MΩ/m
Average Voltage	30 kV
Input power	500 W
Rs/Q	1378.11 Ω/m
Output Energy	90 keV ± 30 keV (β = 0.56)

Sub-harmonic Pre-buncher

Velocity modulation to compress the pulse

- Earliest Particles Slow down
- Latest Particles Speed up

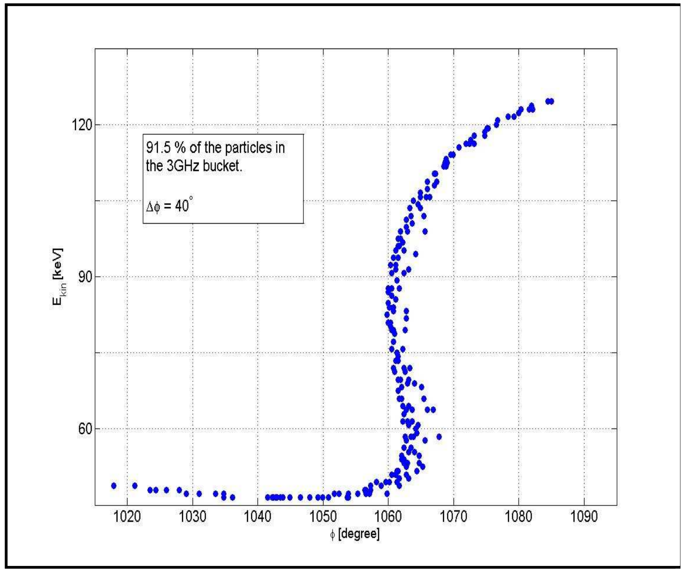
- Beam is bunched
- 500MHz time structure



After a drift space:

$$L_{bunching} = \frac{\lambda_{rf}}{2\pi} \cdot \frac{m_e c^2 \beta^3 \gamma^3}{e\widehat{El}}$$

91.5 % of the particles in one bucket at 3GHz
$\Delta\varphi = 40°$

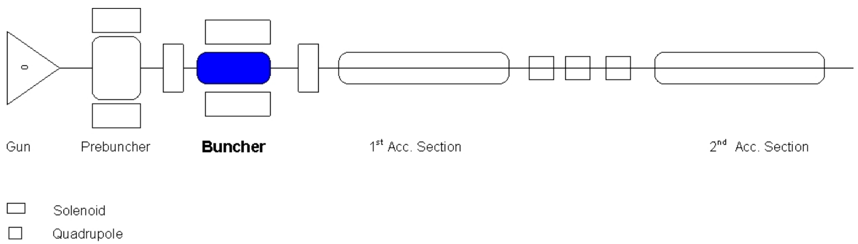


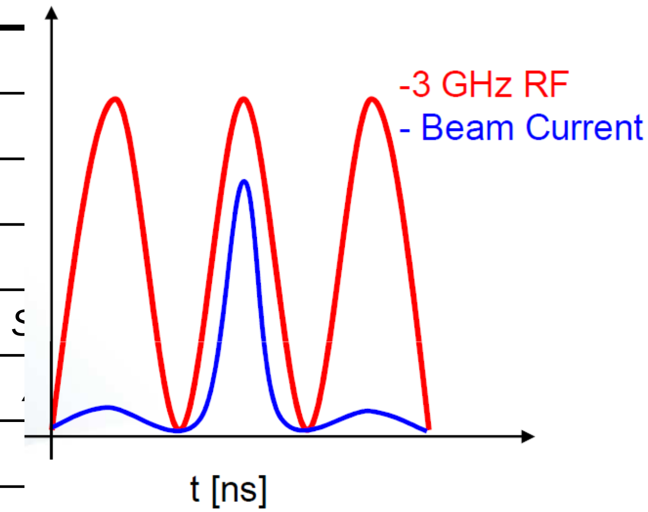
E_{kin} = 90 keV Pulse length = 1ns FWHM

E_{kin} = 90 ± 30 keV Pulse length = 0.22 ns FWHM

- **Notice that the average energy is not changed**
- **NEXT: The beam will increase its energy and will be modulated at 3GHz**

BUNCHER





Filling time – t_f	0.79 µs
Output Energy	~16 MeV

into the accelerating sections.

RF accelerating structures

Standing wave structures

$$E_z(z,t) = E(z)\cos(\omega t + \phi)$$

In a standing wave structure the E-field builds up in time, by multiple reflections

Generally they are multi-cell periodic structures fed by a central coupler

- The central coupler should be matched with the structure in order to avoid reflection at the input port (β=1).

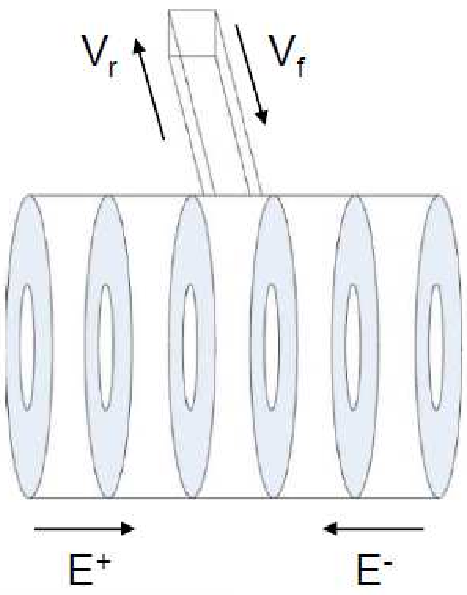
  Nb: In this case β is NOT the relativistic factor!!

- In order to take into account this coupling another paramete is defined:

$$\boxed{\text{Q-loaded factor} \quad Q_L = \frac{Q}{1+\beta}}$$

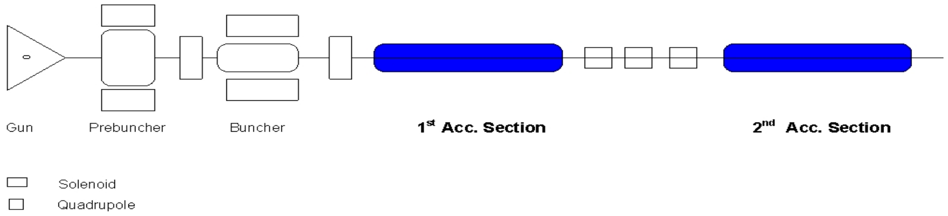
- The energy gain is simply given by:

$$\boxed{\Delta W = qV_0 T\cos\phi}$$



Accelerating Sections

In the ALBA Linac: 2 Accelerating structures increase the energy of the beam



Traveling wave structure with constant gradient

Mode	2/3 π TW const.grad.
No. Cells	96
Total length –L-	3.47 m
Frequency	2997.920 MHz
Shunt impedance –r-	63-69 MΩ/m
Average electric field	10-15 MV/m
Filling time –T_{f}-	0.88 μs
Attenuation -τ-	0.63 neper
Quality factor Q_o	13000
Energy gain (no beam)	55 MeV @ 20 MW

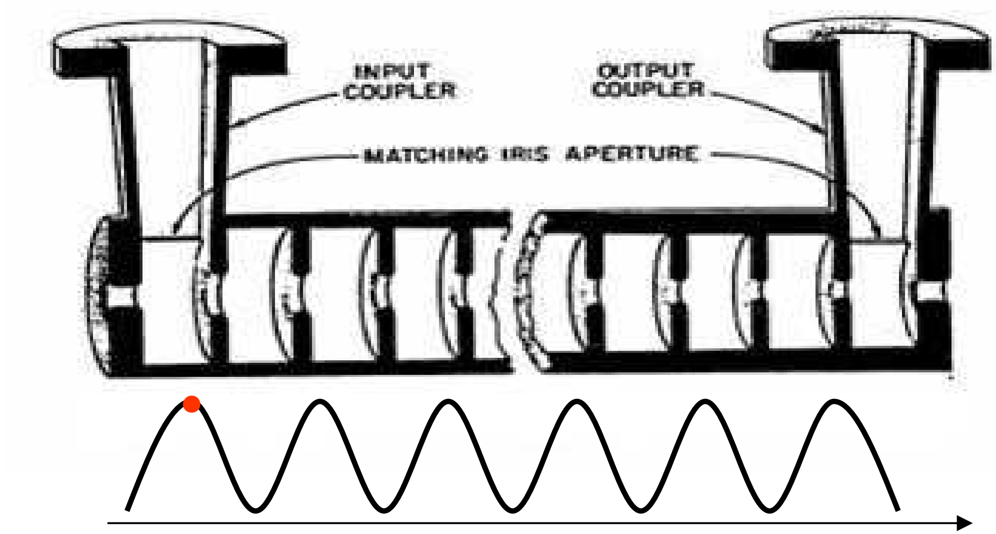
RF accelerating structures

Travelling wave structures

$$E_z(z,t) = E(z)\cos\left[\omega t - \int_0^z k(z)dz + \phi\right]$$

From Klystron P_{in}

P_{out} To absorbing load



- The beam “surfs” on the E-field flowing through the structure.
- The power at the output is dissipated into an external matched load to avoid multiple reflections

RF accelerating structures

Travelling wave structures

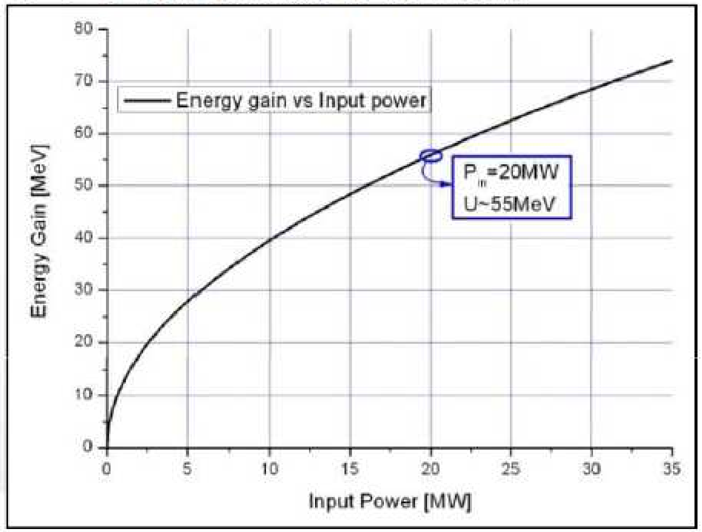
- Constant Gradient

Iris within adjacent cells gets smaller along the structure → E-field on axis is constant

$$\frac{dP_w}{dz} = -2\alpha_0(z)P_w$$

Energy Gain :

$$\Delta W = \sqrt{r_L P_0 L\left(1-e^{-2\tau_0}\right)}\cos\phi;\ [\mathrm{eV}]$$



- Constant Impedance

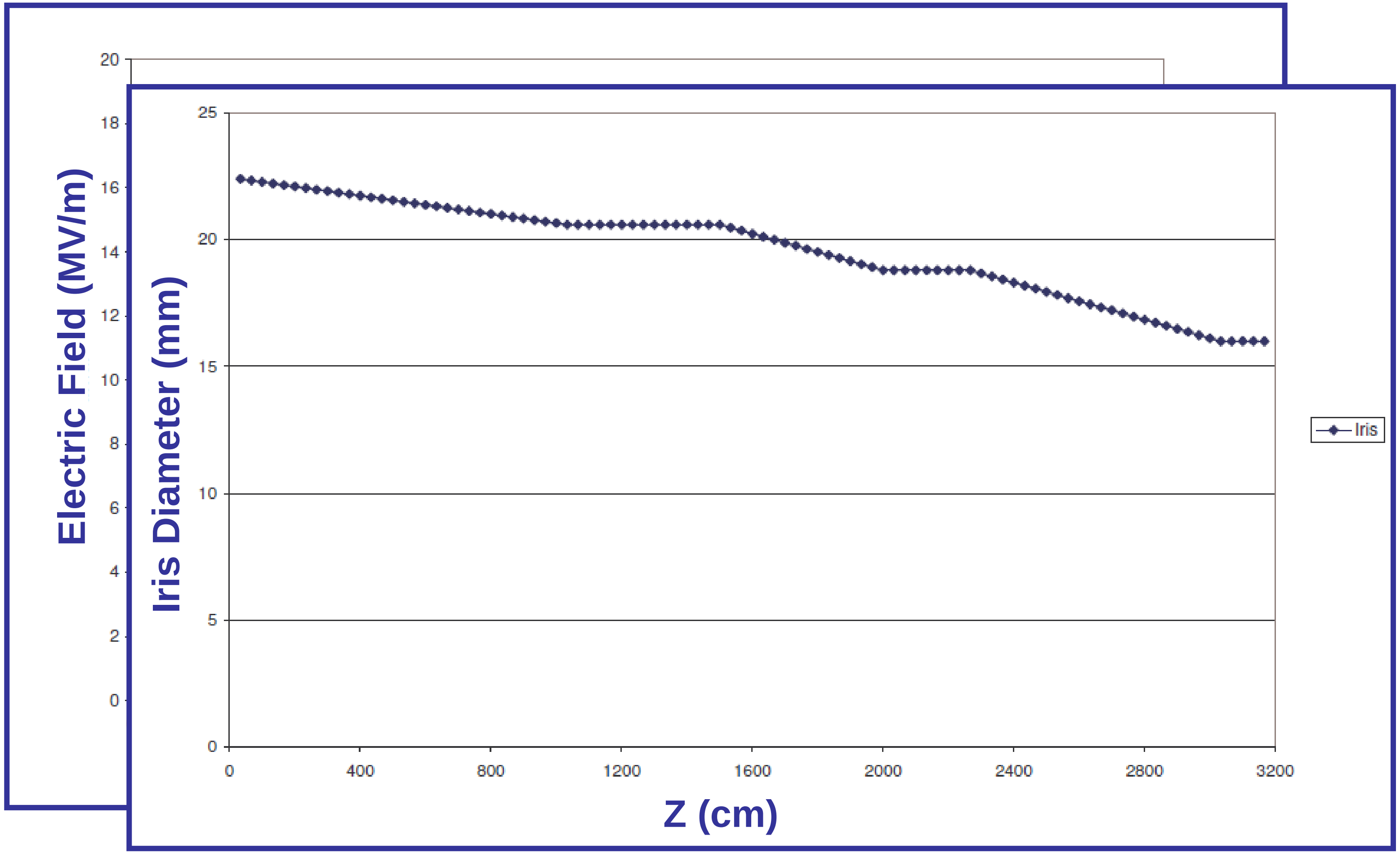
Iris within adjacent cells is constant along the structure → E-field on axis decreases

$$\frac{dP_w}{dz} = -\frac{\omega P_w}{Q v_g}$$

Energy Gain :

$$\Delta W = 0.903 \cdot \sqrt{r_L P_0 L}\cos\phi\ ;[\mathrm{eV}]$$

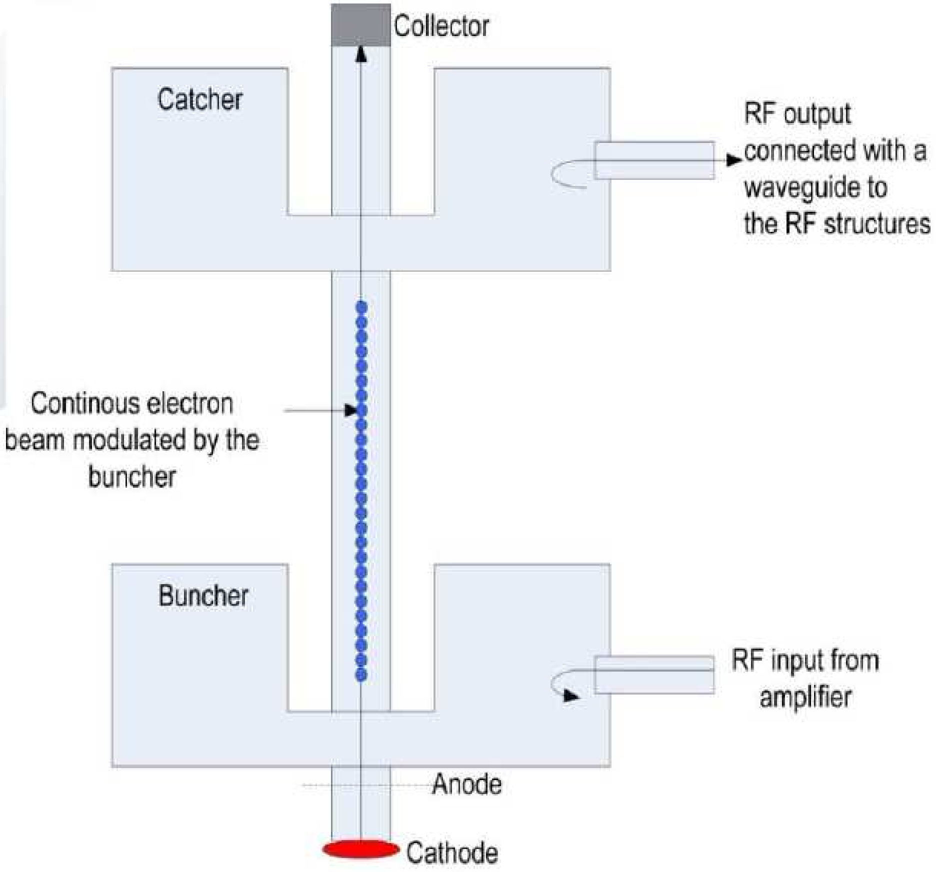
r_L	Shunt impedance per unit length
P_0	Input power
L	Total length
τ_0	Total attenuation
Φ	Phase of beam respect with the crest of the wave


Electric Field (MV/m)
20
18
16
14
12
10
8
6
4
2
0
Iris Diameter (mm)
25
20
15
10
5
0
0
400
800
1200
1600
2000
2400
2800
3200
Z (cm)
Iris

Klystron amplifier

Klystrons amplifiers provide high power EM field for feeding the RF structures.
A klystron can be considered as a "small" linac.

1. A continous electron beam is generated by a cathode.
2. The first cavity ("buncher)" is fed by an antenna and it gives a velocity modulation of the beam.
3. The second cavity ("catcher") is excited by the beam itself.
4. The bunching induces the power amplification.
5. The EM field generated by the beam is picked up, and it is directed to the RF structure through a waveguide.
6. The electrons are then stopped at the collector.



Klystron amplifier

In a klystron amplifier the input power at the buncher is then amplified by the beam through the "bunching" itself.

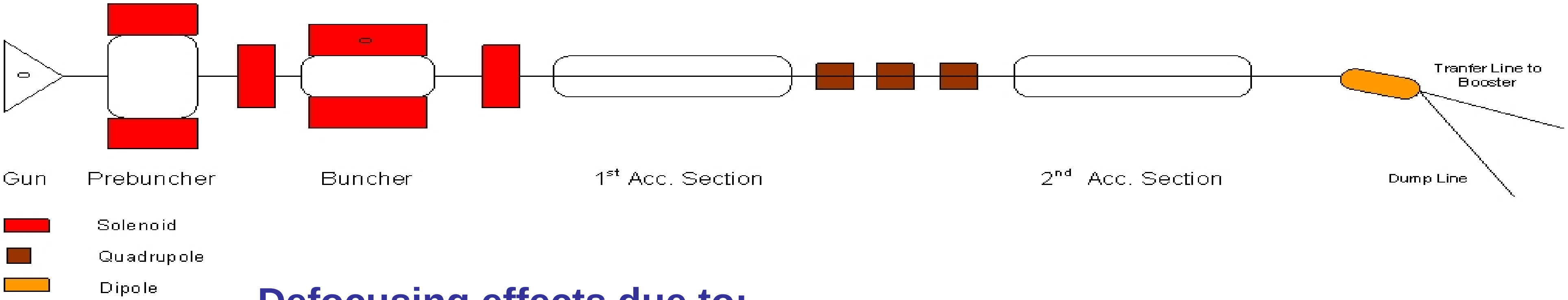
Typical Parameters for a standard klystron amplifier:

Input voltage	280 kV
Output Power (peak)	35 MW
RF pulse length	4.5μs
Frequency	3 GHz

- Questions?

- Tomorrow more about Linac Diagnostics

Magnets

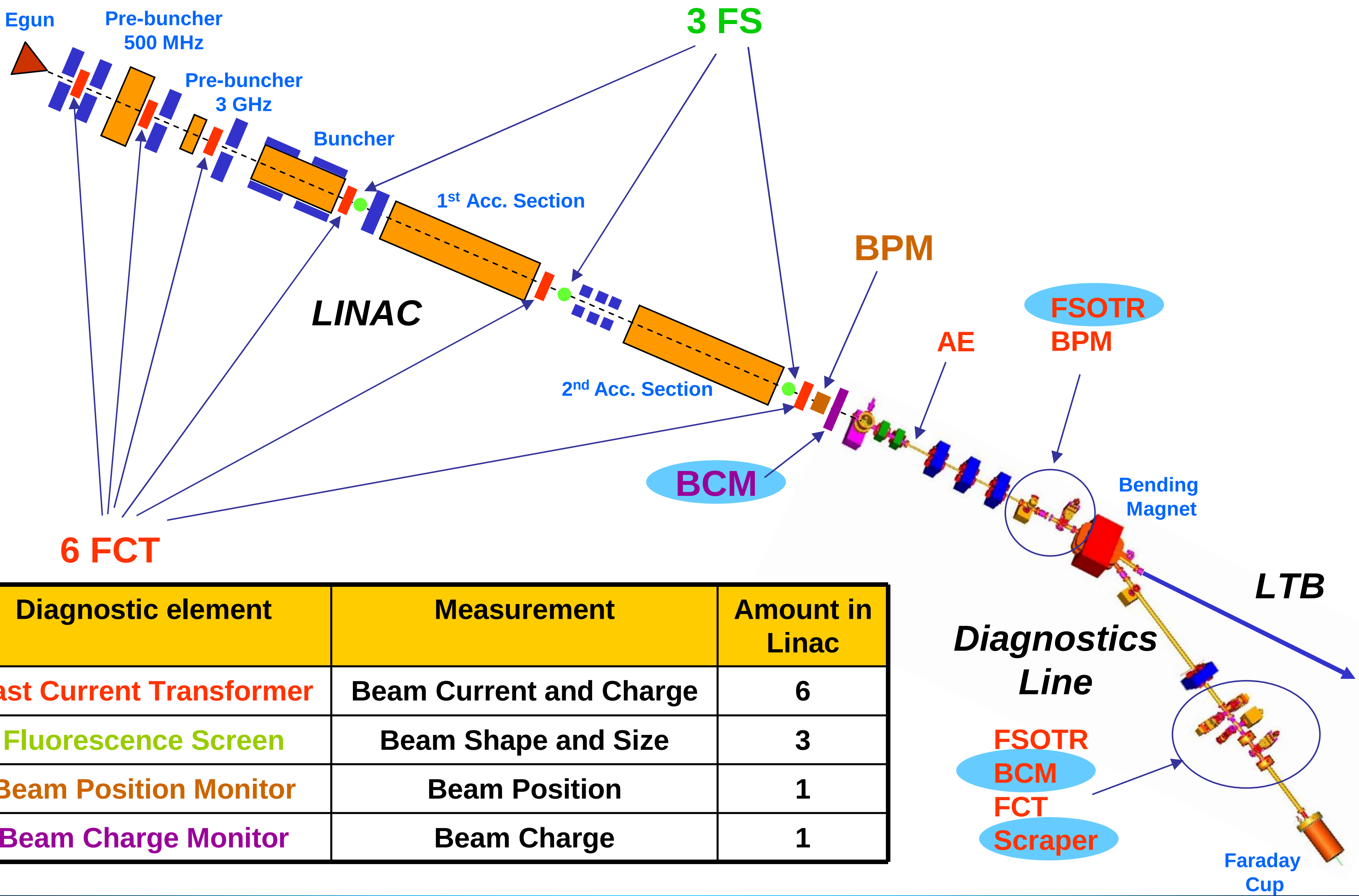


Defocusing effects due to:
- Intrinsic divergence of the beam
- Space charge
- RF defocusing

The beam radius is kept < 2.5 mm by using:
- Solenoids (low energy section)
- Quadrupoles (middle energy section)

Magnets in ALBA Linac:
- 5 solenoid in the bunching section (Shielded)
- 1 triplet of quadrupoles between the two accelerating section
- 1 triplet at the end of the linac
- 1 Bending Magnet to bend the beam to the Transfer Line or to the Diagnostic Line

Diagnostic elements

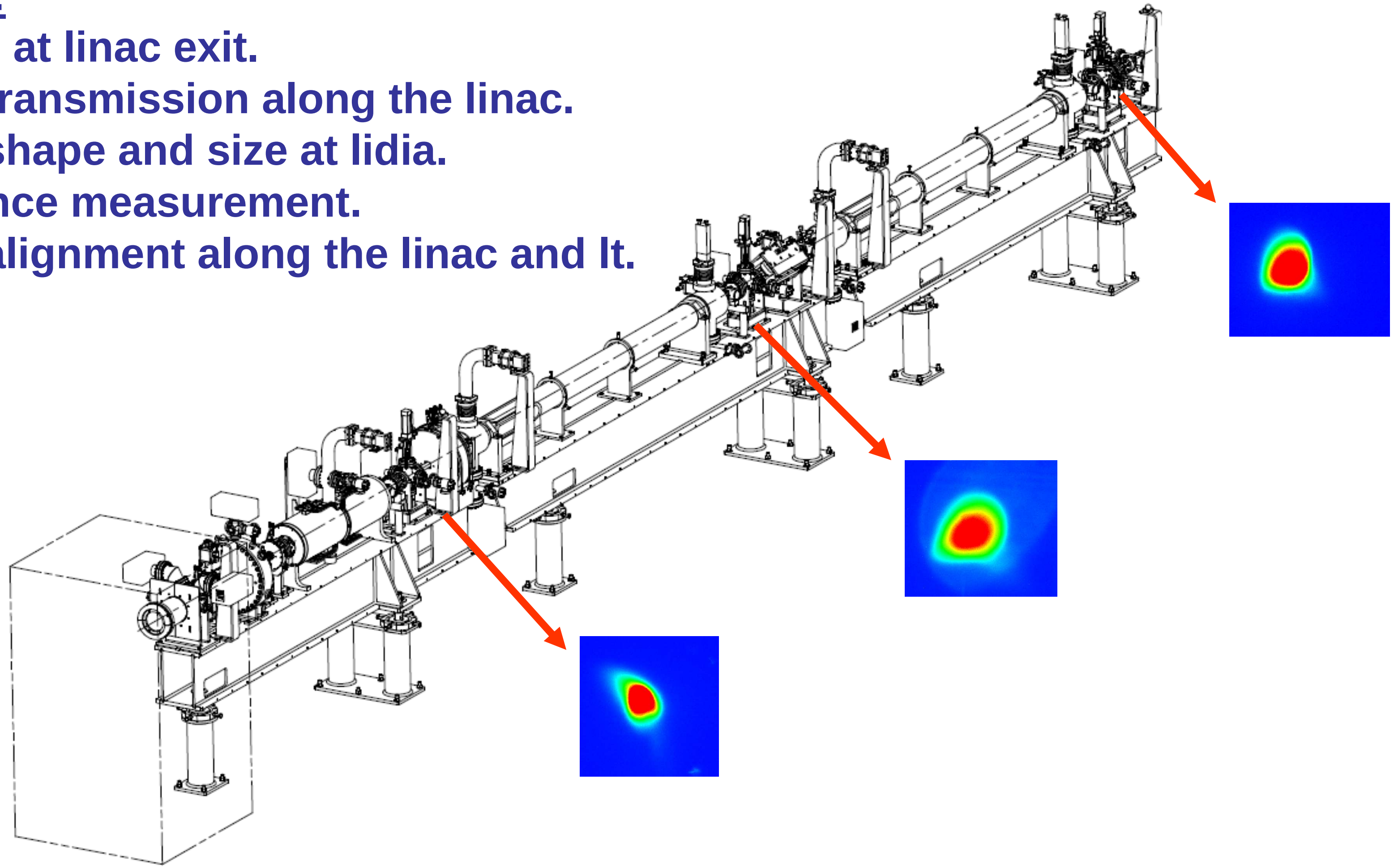


Diagnostic element	Measurement	Amount in Linac
Fast Current Transformer	Beam Current and Charge	6
Fluorescence Screen	Beam Shape and Size	3
Beam Position Monitor	Beam Position	1
Beam Charge Monitor	Beam Charge	1

Beam Optimization

Checks:

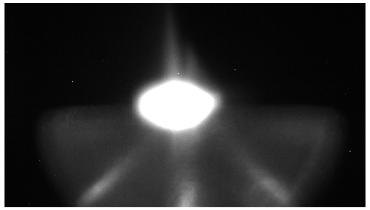
- -Charge at linac exit.
- -Beam transmission along the linac.
- -Beam shape and size at lidia.
- -Emittance measurement.
- -Beam alignment along the linac and lt.



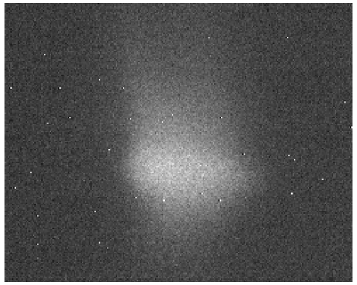
Beam Optimization

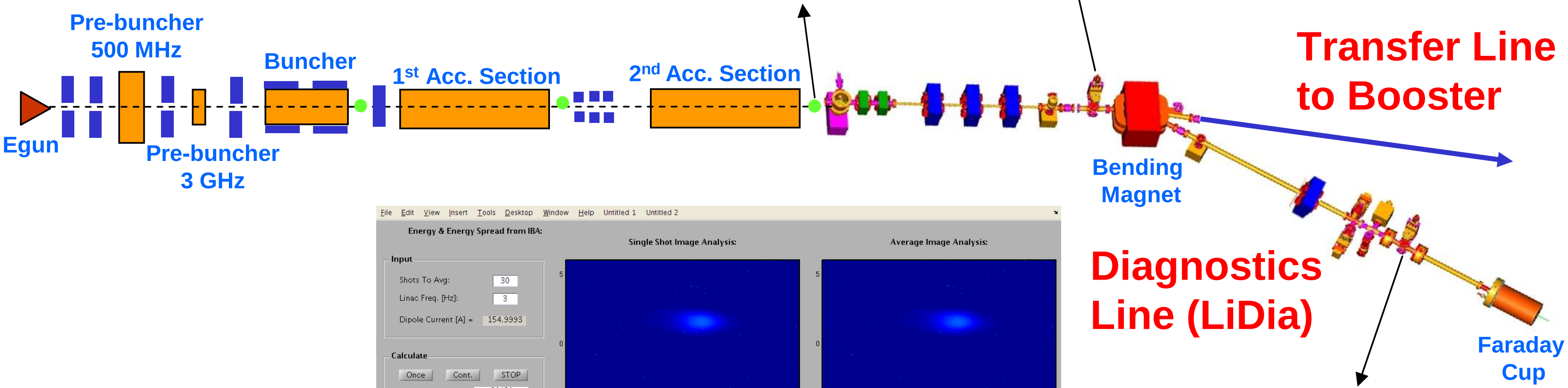
- Round beam at Linac exit

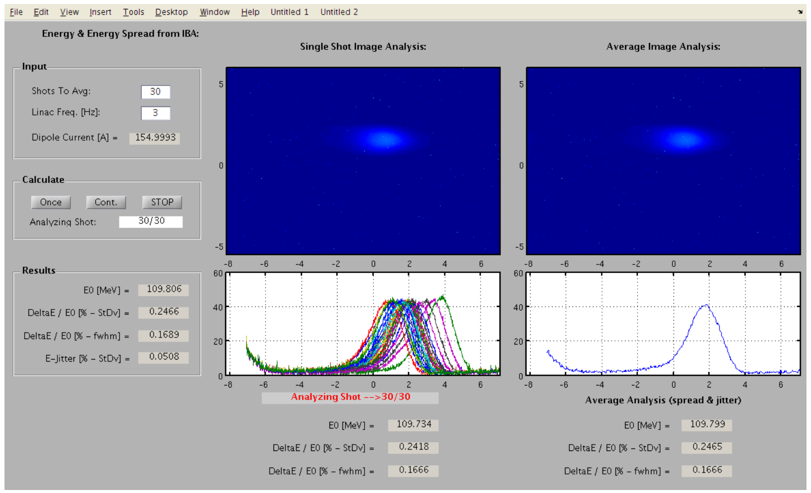
LI-FS-03



LT-FSOTR-01





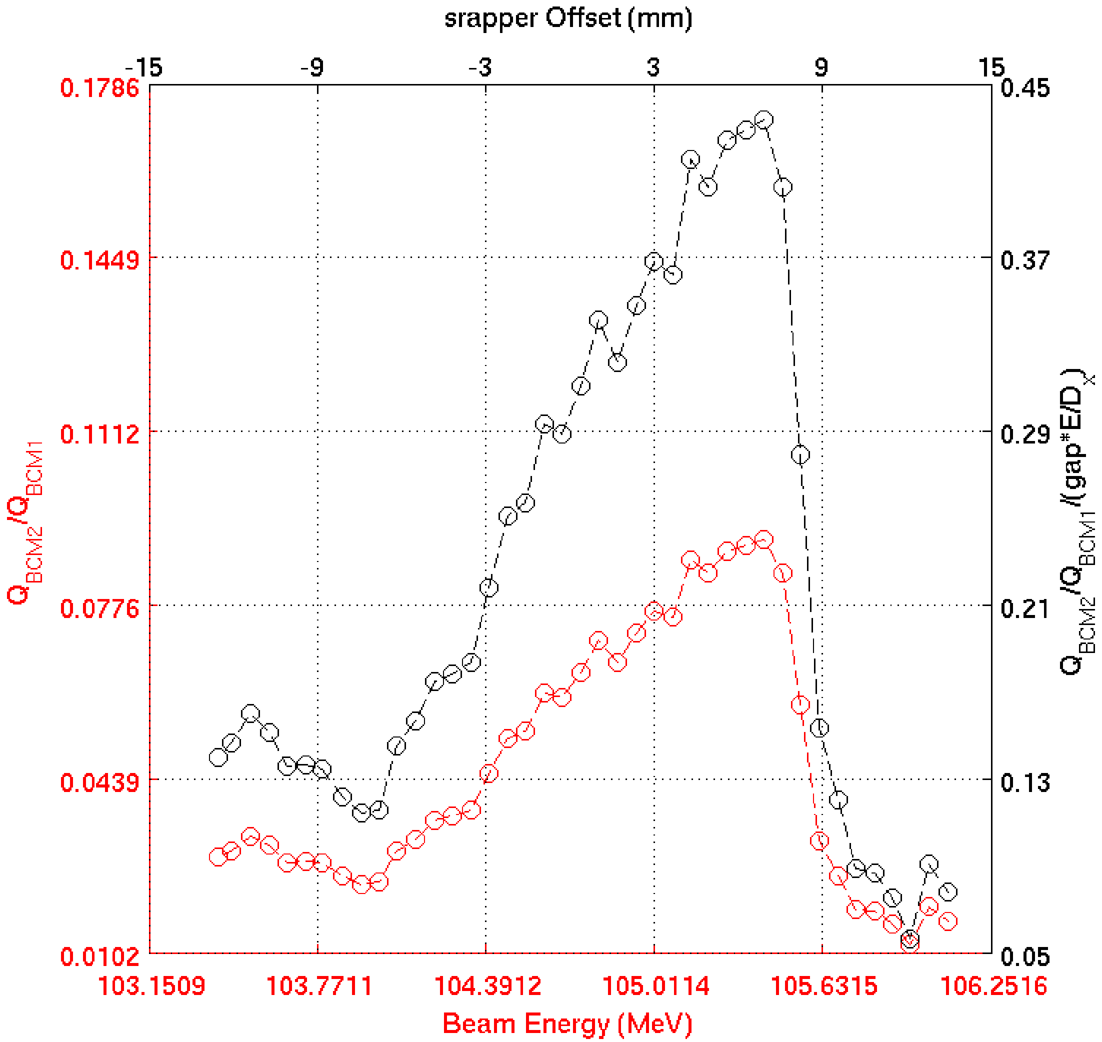


LiDia-FSOTR-01

Fast energy and energy spread measurement

Energy Spread

- **Energy measurement: MBM, 112 ns, 4 nC, 1 Hz**



Scraper offset scanned and recorded BCM2 / BCM1

Results (rms):
E = 104.8 MeV
Energy Spread = 0.62 %

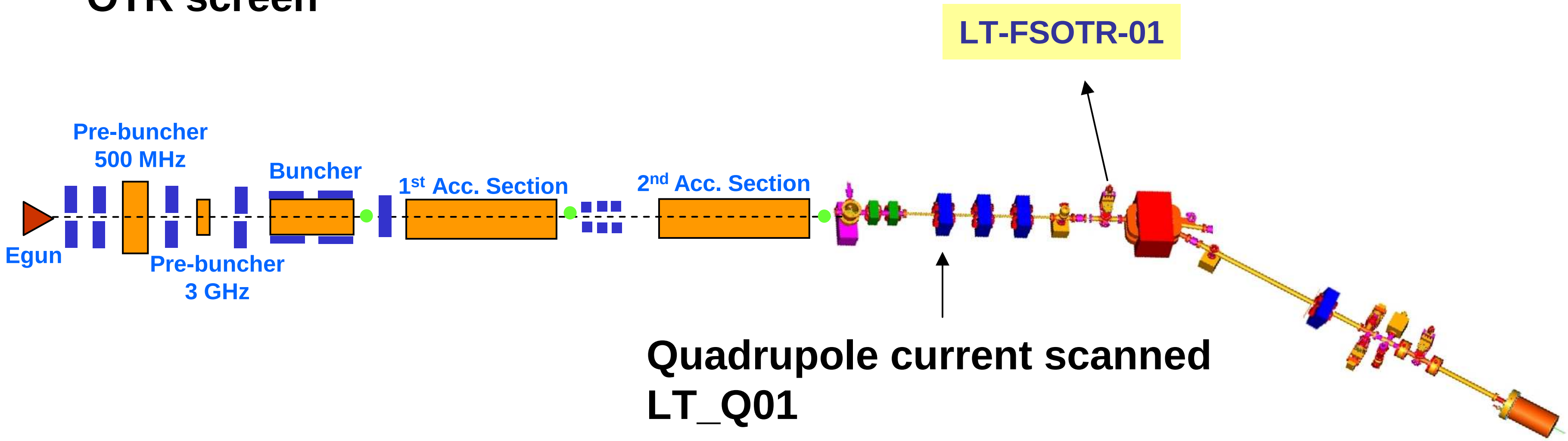
≤ 0.5% in specifications

- **Beam optimization needed**

Emittance

Quadrupole scan method

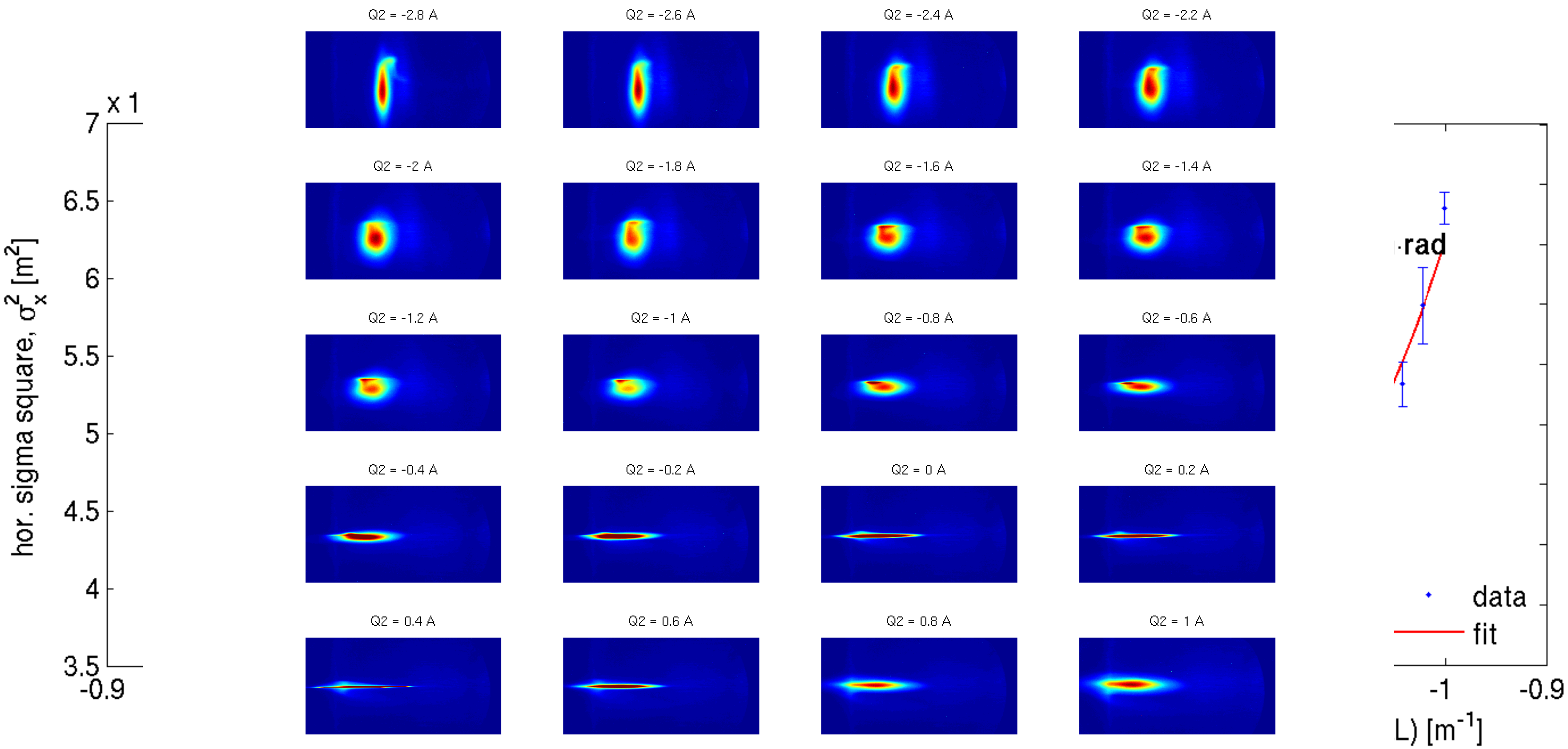
1) Beam size as a function of the quadrupole field strength recorded with OTR screen



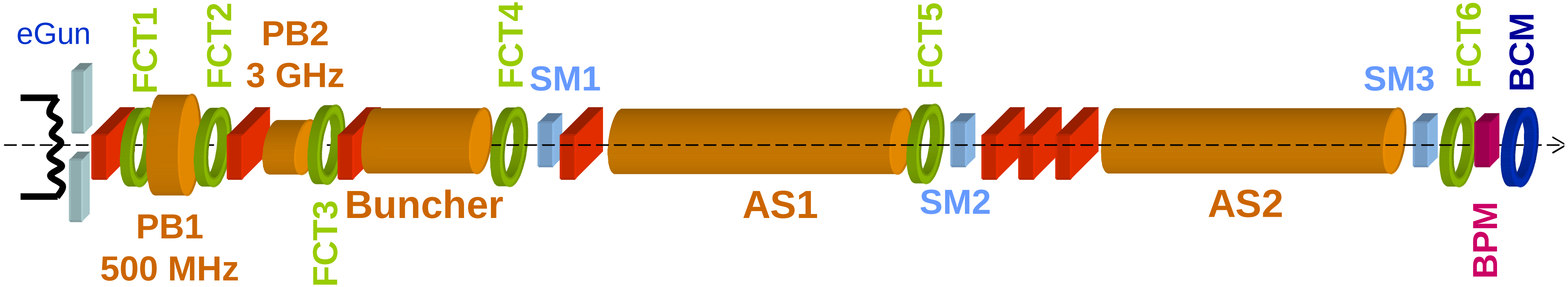
2) Parabola is fitted to extract the emittance from the fit parameters.

Emittance

- **Emittance measurements: MBM, 112 ns, 4 nC, 105 MeV, 1 Hz**



Beam transmission



MBM, measured transmission, 70 MeV

Beam mode	Buncher exit	AS1 exit
500 MHz & 3 GHz	96%	66%
3 GHz	83	58
500 MHz	80	47
No cavities	64	37

General specifications linac ALBA

Parameter @ Linac Exit	SINGLE BUNCH MODE	MULTI BUNCH MODE
Number of Bunches	1 to 16	[18 … 512]
Pulse Length	< 1ns (FWHM)	[36 … 1024] ns
Bunch spacing	6 … 256 ns	2ns (500MHz mod.)
Charge	Q ≥ 1.5 nC	3 ≤ Q ≤ 4 nC
Energy	≥ 100 MeV	≥ 100 MeV
Relative energy spread	≤ 0.5 % (rms)	≤ 0.5 % (rms)
Norm. Emittance (1σ)	≤ 30 π mm mrad	≤ 30 π mm mrad
Energy Variation Pulse-to-Pulse	0.25% (rms)	0.25% (rms)
Beam position stability pulse-to-pulse	<10% of beam size	<10% of beam size
Jitter pulse-to-pulse	≤ 100 ps (rms)	≤ 100 ps (rms)
Single bunch purity	Better than 1%	…
Repetition rate	1 to 5 Hz	1 to 5 Hz

Bibliography

1) T.Wangler, "*RF Linear Accelerator*" (Wiley, New York 1998)

2) P.Lapostolle, "*Linear Accelerator*" (A.Septier, North Holland, 1970)

3) M.Puglisi, "*The Linear Accelerator*" in "*Principles of particle accelerators*" (W.A.Benjamin, New York, 1968)

4) I.M.Kapchinskii, "*Theory of resonance linear accelerator*" (Harwood, Chur, 1985)

5) Cern Accelerator School, "*Fifth general accelerator physics course*" (S.Turner, 1992)

6) Cern Accelerator School, "*RF engineering for particle accelerators*" (S.Turner, 1991)