Microwave Generators for Application to Particle Accelerators and Ion Sources: Klystrons, other Vacuum Tubes and Solid State Amplifiers*

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1) *Introduction*
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Powerful radiofrequency (rf) and microwave generator are of widespread in particle accelerators and sources, for the lower voltages required by rf accelerators as compared to electrostatic ones (which have a better power efficiency). Large accelerator projects request efficiency optimization, especially promising in the case of klystrons, where efficiency is determined by the intermediate cavity tunings, and for large tube ratings (multiMW), by the self electrostatic potential of the electron beam itself. Tubes with many electron beamlets are an option to mitigate this effect. Also modern developments in computational physics offer the possibility to study and improve the klystron bunching mechanism more directly, and general features and trends are discussed. The gyrotron and applications to ion sources are also summarized.

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1) INTRODUCTION:

Particle accelerators over 1 MeV energy (as an order of magnitude) typically uses microwaves (in general radiofrequency), to limit insulation problems.

Particle accelerators below 1 MeV energy often uses electrostatic acceleration, which have a greater accelerator efficiency (in principle $\eta_a \cong 1$), defined as

$$\eta_a = K_1 I_b / |q| P_a$$

***K_1* kinetic energy of particle**

***I_b* total beam current, with q and m the particle charge and rest mass**

***P_a* electrical power applied to accelerator**

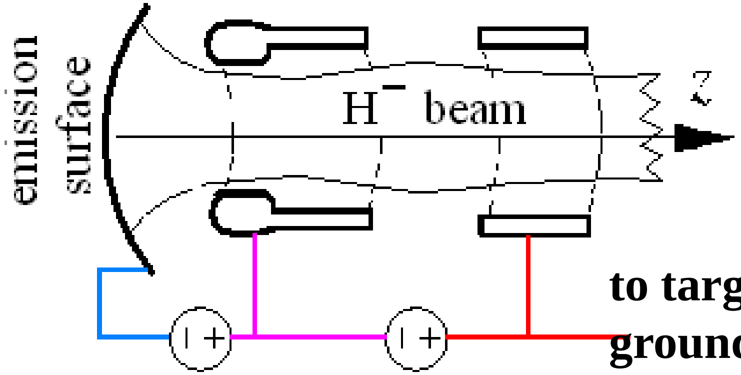


Figure 1 electrostatic accelerator (two gaps shown)

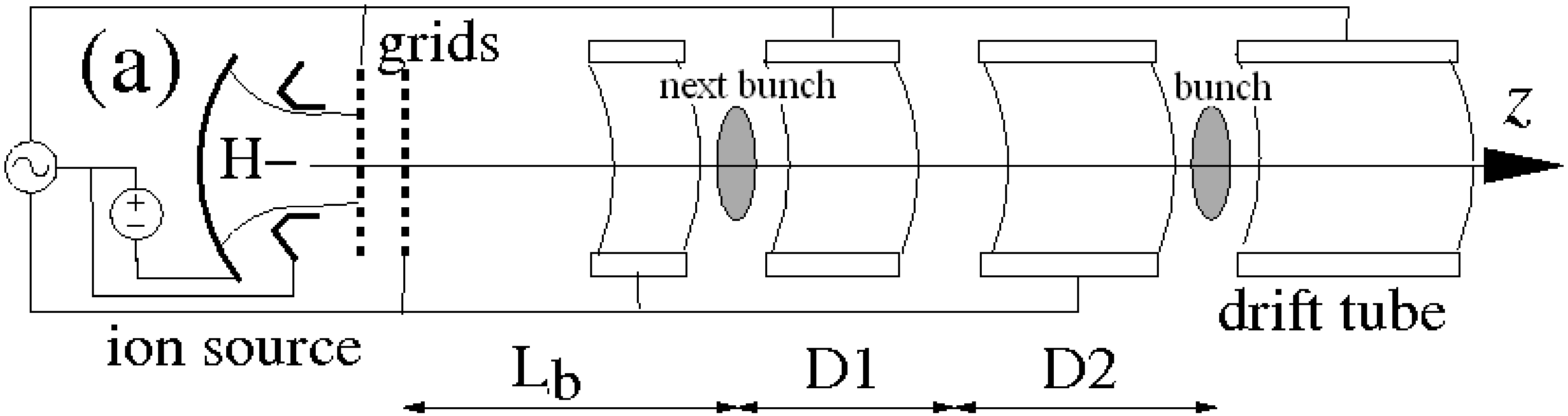


Figure 2 Wideroe radiofrequency accelerator; ion source acceleration is also schematized

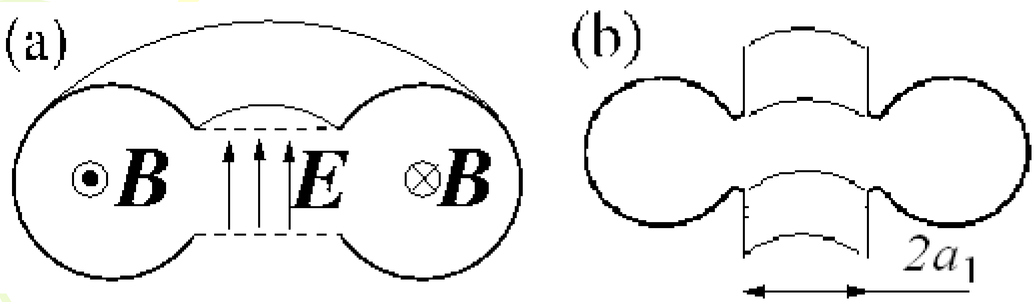


Figure 3: (a) resonator (or a resonating cavity, originally called *rhumbatron*, Hansen, 1938): klystron concept requires storage of energy in a resonator to build a strong output voltage V_N; (b) open cavity; (c) klystron

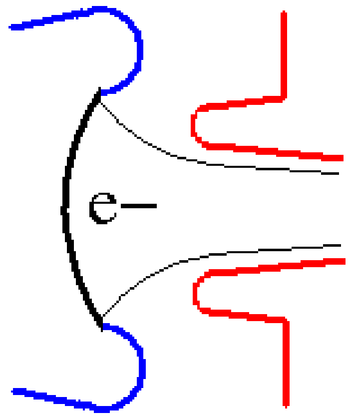
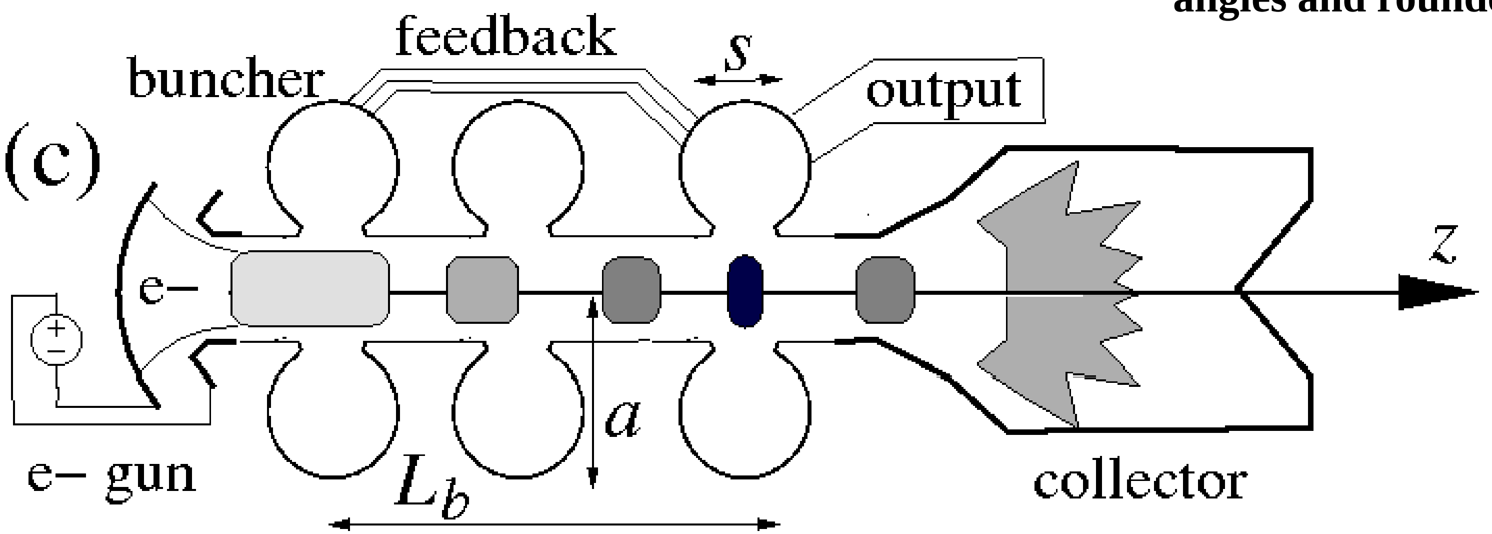


Figure 4: e-gun (with typical angles and rounded electrodes)



Klystron principle [Varian, 1939]: a constant electron current I_b is accelerated electrostatically in a so called e-gun (improved by [Pierce, 1954]) by static voltage V_0. A 1st rf cavity accelerates and decelerates these electrons with a small oscillating voltage V_1; after a distance L_b electrons group in bunches, which passes in the output cavity when its field V_N is decelerating electrons (by adequate design). Feedback from V_N to V_1 may improve gain or make an oscillator. Magnetic focusing (not shown) is applied (at least in the L_b region)

In other words, klystron modulates electron density and so current develops harmonics

$$I_t = I(z = L, t) \cong \frac{I_b}{1 - B\cos(\omega t - \psi_0)} \quad , \quad B \leq 1$$

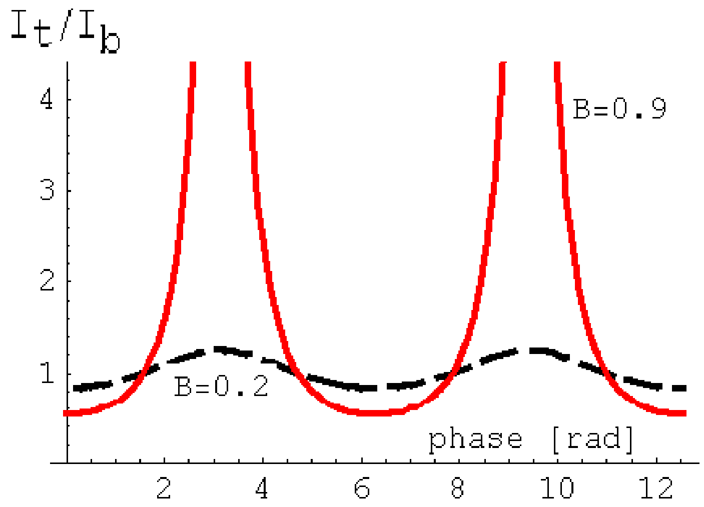


Figure 5: plot of the current modulation (klystron), depending on bunching factor B

$$B = T_{TF}\frac{|V_1|\omega L}{2u_0 V_0}$$ **bunching parameter (two-cavity and Non -relativistic expressions are used, if not otherwise stated)**

$$\psi_0 = \omega L/u_0$$ **phase shift respect to 1st cavity**

u_0 beam speed at e-gun exit, ω angular frequency, V_0 e-gun voltage, V_1 buncher voltage, T_{TF} (see later) is about 1

Bunching distance $L=L_b$ is such that B is about 1

A Klystrode modulates electron <u>current</u> with a grid in the e-gun as in triodes (see figure) , but has cavity(s) for microwave output as a klystron.

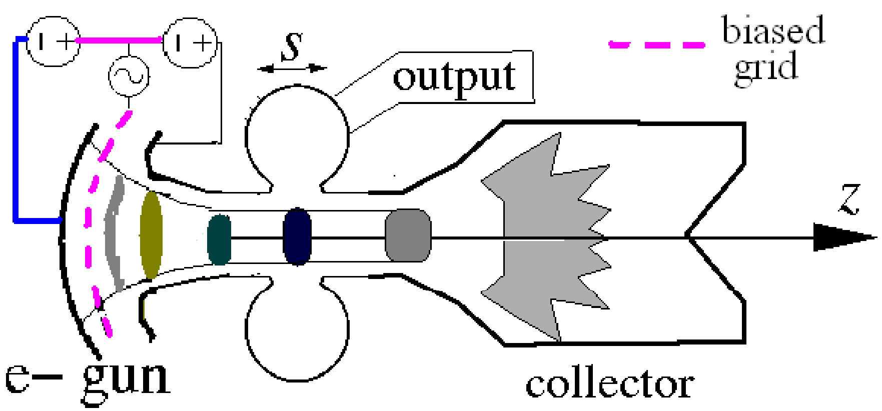


Figure 6: klystrode →

Klystrodes (aka IOT, inductive output tube) are not inefficient when only a fraction of maximum power is required; but they are limited in frequency (<1.3 GHz) and durability by the grid electrode.

2) Example of linacs, rf generators and accelerating structures

(note: special electrostatic accelerator up to 25 MeV are used in nuclear physics, but for very limited current)

(1) Proton linac LAMPF (Los Alamos, 1972) ; not only protons (H+ or p) but also H- (hydrogen negative ion) can be accelerated to K_1=800 MeV, with same 805 MHz rf power supply (another advantage of radiofrequency versus electrostatic); no wire connection to electrodes is necessary (as it was in Wideroe linac), but microwave power is fed by a few lateral ports, and travels from one cell to cell to another.

Cells are grouped into (linac) modules, each one with a few microwave in/out ports.

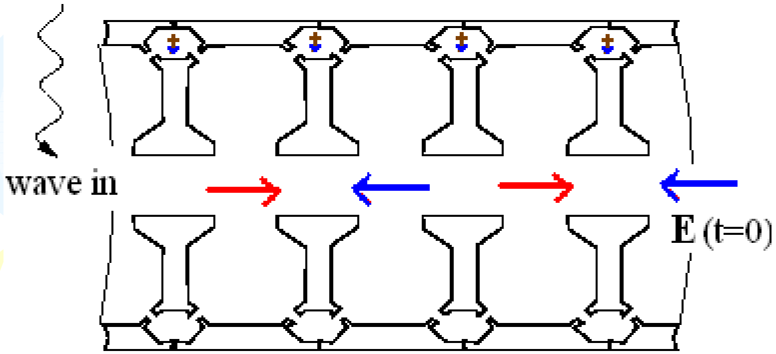


Figure 7: a cavity coupled linac (LAMPF), with lateral coupling cavity

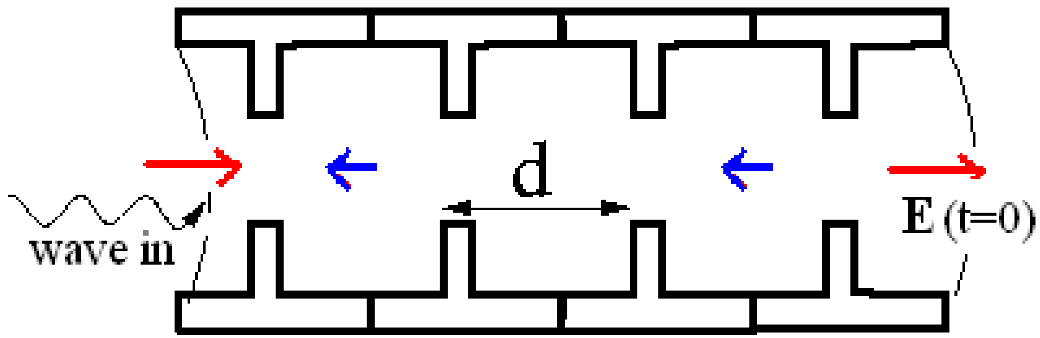


Figure 8: an iris coupled travelling wave linac (SLC)

(2) Stanford Linear collider SLC (1987); both electrons and positrons (e+) are accelerated up to 50 GeV (50000 MeV); the 2.856 GHz microwave travels inside a tube with periodically repeated irises, with a phase advance of $2\pi/3$ per cell

Table I: linac and klystron parameters

	LAMPF	SLC (Stanford Linear Collider)	CLIC service linacs for primary beam	CLIC main linacs
Year	1972	1987	design 2012	design 2012
Number of linacs	1	1	2	2
Length/linac [km]	0.8	3.2	2.5	15
particle kinds	p, H-	e, e+	e	e, e+
final energy [Gev]	0.8	50	2.37	1500
frequency f [GHz]	0.805	2.856	0.9995	11.994
phase advance per cavity [deg]	90	120	120	120
max radius / wavelength a/λ	0.4	0.39	0.38	0.11 (b)
number of klystrons	44	200	819	35808
rf power(pulsed)/klystron [MW]	1.25	> 50	15	134
klystron pulse duration	1 ms	0.0035 ms	0.142 ms	176 ns
klystron voltage	86 kV	315 kV	150 kV	2370 MV (b)
klystron beam current I_b [A]	28	354	140 (a)	101
klystron DC to rf efficiency	0.57	> 0.45	0.7	0.95 (c)

Notes: (a) total current in klystron (here a multi beam klystron with 7 beamlets) ; (b) PETS (Power Extraction and Transfer Structure) , conceptually equivalent to a klystron output cavities, are used instead of klystrons; primary beam voltage is reported as klystron voltage; (c) excluding losses for primary beam generation and dump (d) in the simpler analytical model (a long cylinder) it holds a/λ=0.383…

(3) MUNES (MUltidisciplinary NEutron Source, INFN, in construction). This project aims to develop a 5 MeV/ 30 mA proton compact proton accelerator for medical and industrial application (with 100 % duty cycle, that is CW regime). Due to large current, the accelerator structure is made of Radiofrequency quadrupole (RFQ) modules, each requiring 125 kW CW radiofrequency power at 352 MHz

In principle, a single 1.3 MHz klystron can power all modules, with a large power splitting network (this klystron comes from the LEP, Large Electron-Positron collider, 1989; see data for its efficiency in figure on slide 12)

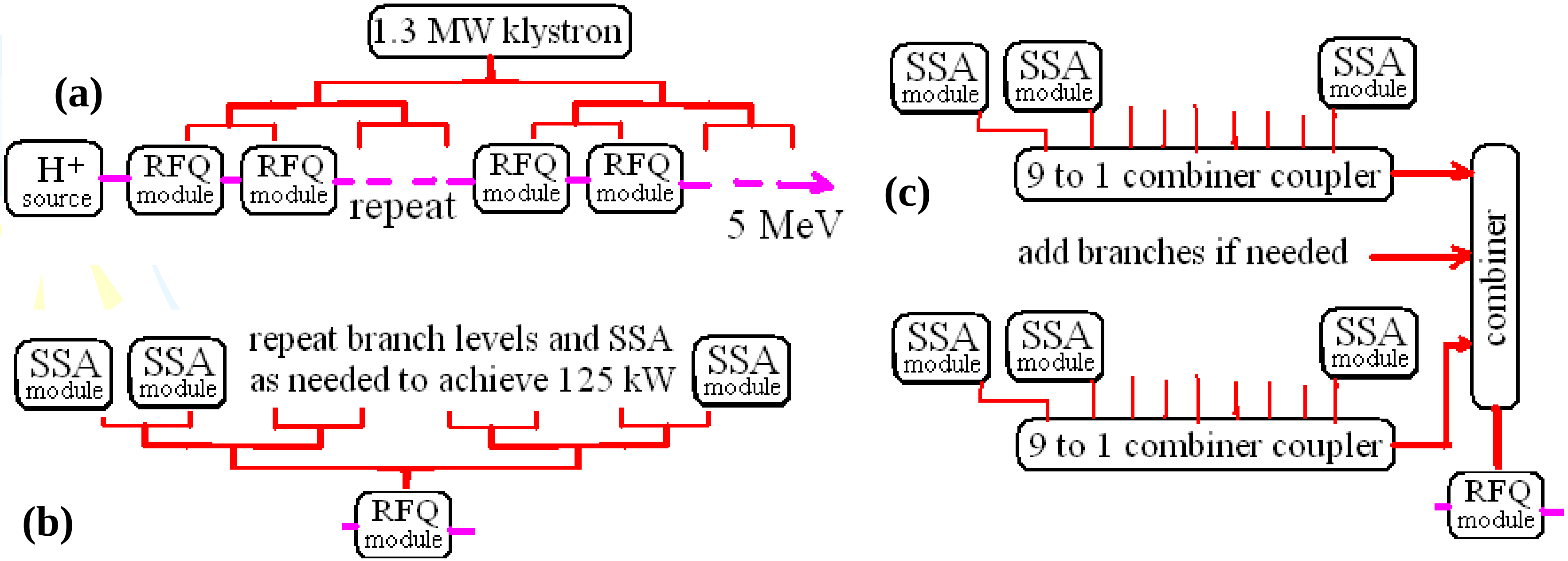


Figure 9: (a) Power splitting scheme; (b) 2 to 1 iterative power combining; (c) matrix power combining

Conversely, each 125 kW module can be powered by solid state amplifiers (SSA), each providing a few kW, with a power combination network. This avoid the still large voltages involved with klystron and decrease maintenance cost. For the steady progress in solid state, this solution may be expected to become typical for this accelerator class (low energy, high current); see Ref [4] and [19].

(4) CLIC (Compact LInear Collider, conceptual design updated in 2012), a so called two-beam accelerator. Klystrons are partly replaced by PETS (Power Extraction and Transfer Structure) , a passive structure extracting rf power from a primary electron beam (2.37 GeV) ; this rf energizes the main linac modules (where electron and positrons are supposed to accelerated to 1500 GeV)

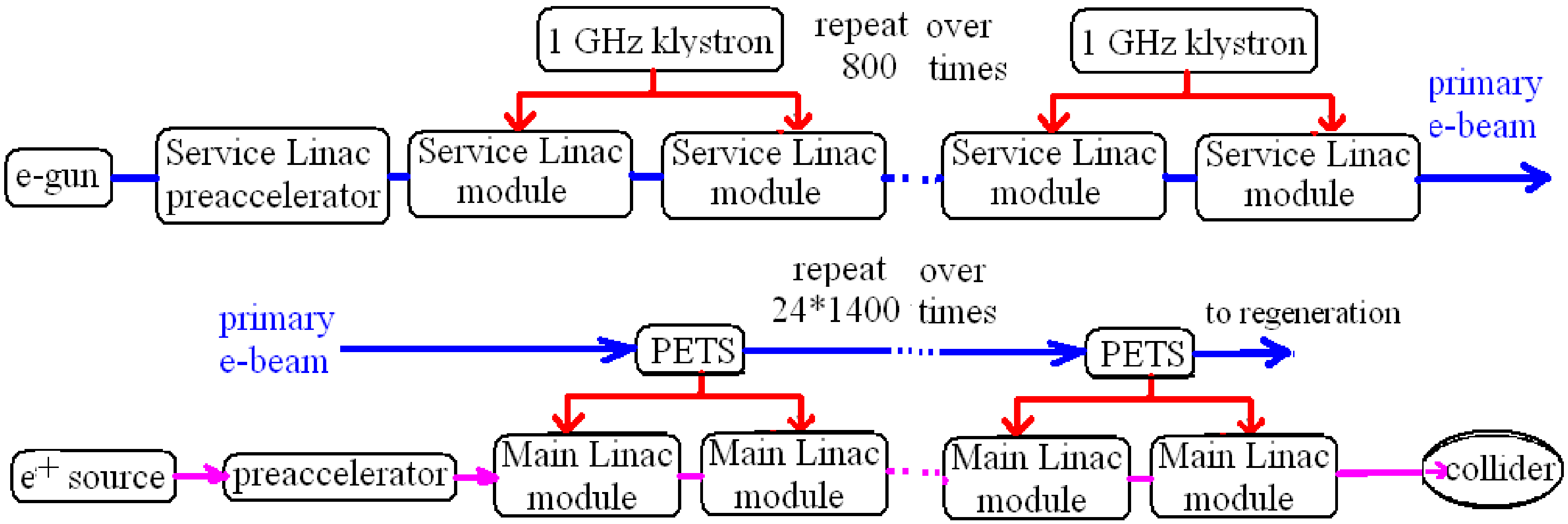


Figure 10: the two-beam accelerator concept; energy transfer (with time compression, see table I) is from klystrons to primary beam to PETS to colliding beams

3) Some theory on bunching, linacs, klystron efficiency and TWT

Assume particle are well focused in x, y, so that only z motion need to be studied in a first approximation → 1 D model (z,t): arrival time is

$$t_a(z,t_0) = t_0 + \int \mathrm{d}z/v_z$$

where v_z depends from start time t_0 (passage from middle plane of some cavity, usually the buncher)

Timing of rf phase and particle time is extremely important; for example in the Wideroe linac, resonance condition:

$$\frac{D_1}{v_1} + \frac{D_2}{v_2} \cong \frac{2\pi}{\omega}$$

Angular frequency $\omega = 2\pi f$

Velocity v_z after e-gun = v_0

Velocity v_z after first gap = v_1, and so on

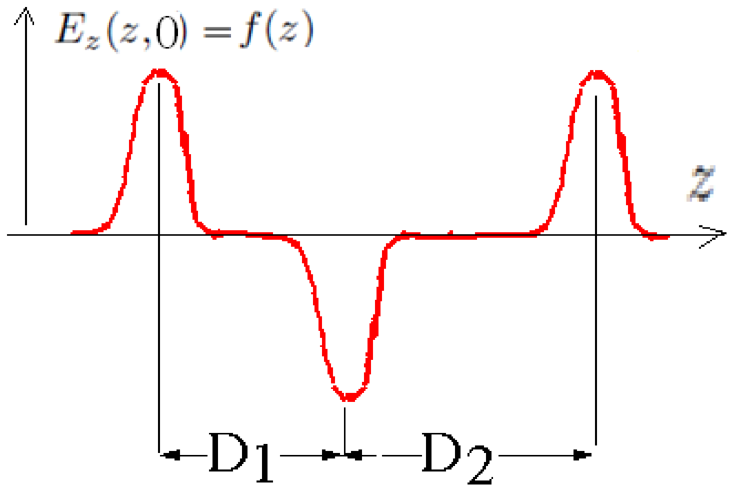


Figure 11: E_z field in the Wideroe ion Linac (for ϕ_0=0=t)

Standing wave structures: $E_z(z,t) = f(z)\cos(\omega t - \phi_0)$, $f(z) = e(z)\cos(\phi_1(z))$

where $e(z) \geq 0$ **and phase increases monotonically by 180^0 (that is 3.1415.. radians) each E_z sign change** $\phi_1(z) = \int_0^z \mathrm{d}z\, k(z)$ $\qquad k(z) \cong \pi/D_i$

Travelling wave structures

$$E_z(z,t) = e(z)\cos\psi \quad , \quad \psi(z,t) = \omega t - \phi_0 - \phi_1(z)$$

phase advance $\psi_a = \psi(z,t) - \psi(z+d,t)$

3.1 coupling between electron and cavity

Transit time factor (T_{TF}): during travel inside a cavity, field E_z changes, so particle acceleration voltage V_{eff} is typically less than total cavity voltage V_1, even for the most accelerated particle that happens to pass cavity middle plane when field is maximum. In the case of small signal s, v_z is only slightly perturbed; so define wavenumbers:

$$k_e = \omega / v_z \quad , \quad k_0 = \omega / c \quad , \quad \gamma_t = \sqrt{k_e^2 - k_0^2}$$

$$V_{eff}(k_e) = \int \mathrm{d}z f(z) \mathrm{e}^{-\mathrm{i}k_e z} \quad , \quad V_1 = \int \mathrm{d}z f(z) = V_{eff}(0)$$

$$T_{TF}(k_e) = \frac{V_{eff}(k_e)}{V_1} = J_0\left(\frac{k_e s}{2}\right) \frac{I_0(\gamma_t r)}{I_0(\gamma_t a_1)}$$

In klystron cavities, a T_{TF} near 1 is desired (for good coupling of rf and beam):

so $k_e\, s < \pi/4$ is a usual design rule (note J0(π/8)=0.96 ..).

Similarly $k_e\, a_1 < 0.5$

3.2) The klystron efficiency question

$$\eta_k \equiv \frac{P_m}{I_b V_0}$$

P_m = power converted from e kinetic energy to microwave

$V_N = -V_c \cos(\omega t - \psi_0)$ **V_c = amplitude of last cavity voltage V_N; with phasors** $V_c = |V_N|$

Let h_1 the fraction of electron in the bunch (that is, with phase such to be decelerated by V_N); to avoid reflection we need $V_c/V_0 < 1$

Let h_{-1} the fraction of electron with the opposite phase; they are accelerated to an energy

$$K \cong e(V_0 + V_c)$$

Let h_0 the fraction of electron with intermediate phase (whose kinetic energy is not affected) $h_0 + h_1 + h_{-1} = 1$

1D Estimate (for very good bunching, many cavity klystrons, with improved output cavities)

$$\eta_k \cong (h_1 - h_{-1}) \frac{V_c}{V_0}$$

With some opti-mism, η_κ >= 90 % seems possible

For two-cavity bunching scheme, T_{TF}=1 approximation, we can make a Fourier analysis of I_t

$$I_t = I_b + 2 I_b \sum_{n=1}^{\infty} J_n(nB) \cos n(\omega t - \psi_0)$$

$$P_m = -\langle I_t V_N \rangle = I_b V_c J_1(B)$$

$$\eta_k = \frac{J_1(B) V_c}{V_0} \leq 0.582$$

(Naive two-cavity upper bound, now obsolete for N cavities)

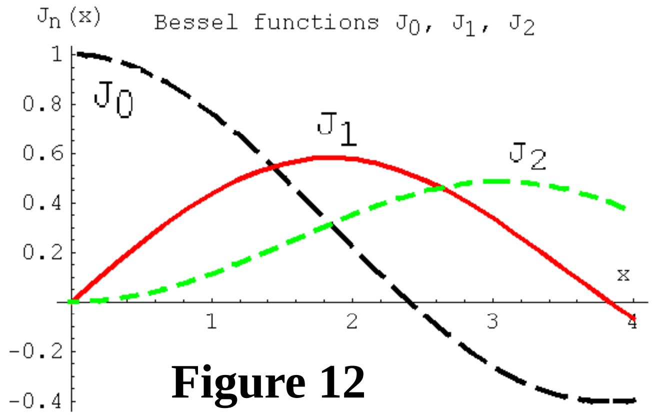
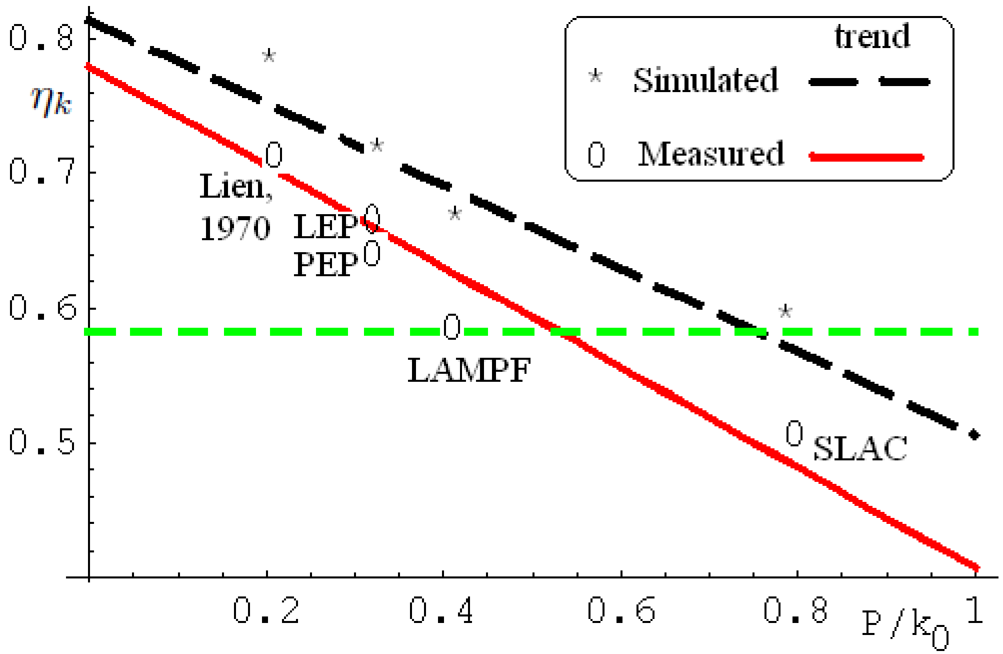


Figure 12



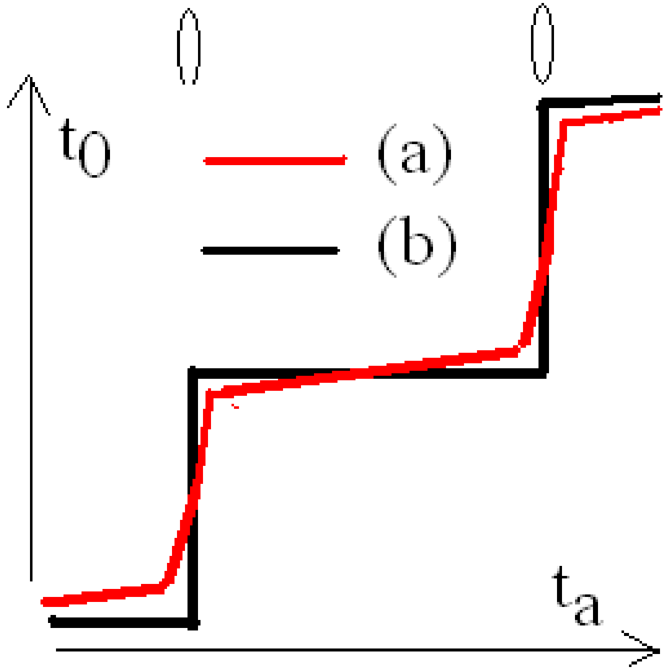
$$\eta_k^{sym1} = 0.814 - 0.308(P/k_0)$$

$$\eta_k^{exp} = 0.78 - 0.373(P/k_0)$$

Figure 13: examples of simulated and measured klystron efficiency (see Ref [20], 1979, and references there within, except for LEP) and trends; here <u>perveance</u> P is scaled by constant k_0

$$P = \frac{I_b}{V_0^{3/2}} \quad , \quad k_0 = \frac{4\epsilon_0}{9}\sqrt{\frac{2|q|}{m}}$$

Space charge opposes to bunch compression, reducing efficiency in most cases; some balancing of it and nonlinearities was also proposed [13]



$$t_a(z, t_0) = t_0 + \int dz/v_z$$

Figure 14: t_0 vs arrival time t_a (a) optimal bunching at output cavity (aiming at η=0.9 , see [13]); (b) sawtooth buncher (unrealistic case)

Table II: a checklist of simple solution principles in klystron design

Problem	Remedy
Electron loss on tube walls	Improve magnetic field of solenoid or use the alternating sign permanent magnet focussing
Amplification (gain) is less than required	Add intermediate cavity
Bunch current not uniform	Add double frequency intermediate cavity (a cavity resonant to 2 ω)
Fringe field of output cavity voltage Vc reaccelerates beam in collector	Divide output cavity into two cavities, so that Vc is less
Output cavity voltage Vc is so large to give arcs	Make a multigap output cavity, which is longer and reduces electric field (a) (b)
For the required power level, perveance(space charge) results too large to reach goal for efficincy	(1) Increase e-gun voltage V0
	(2) divide total beam current Ib into n e-guns, making n beamlet independently focused and travelling parellel, into the same output cavity (multi beam klystron, MBK)
	(3) use a so called sheet electron beam, that is a rectangular section beam with Ly >> Lx (sheet beam klystron, SBK)

(a) This also add to klystron some similarity to TWT (see later), with some improvement of the bandwidth (b) for example of a seven gap output cavity (about 1.5 cm total length, for a 50 kW peak rf 95 GHz sheet beam klystron project) see fig 3 in Ref [23]: G Scheitrum, G. Caryotakis, A. Jensen, A. Burke, A. Haase, E. Jongewaard, M. Neubauer, B.Steele "Fabrication and Testing of a W-band Sheet Beam Klystron" 1-4244-0633-1/07 2007 IEEE

3.3) TWT and bandwidth

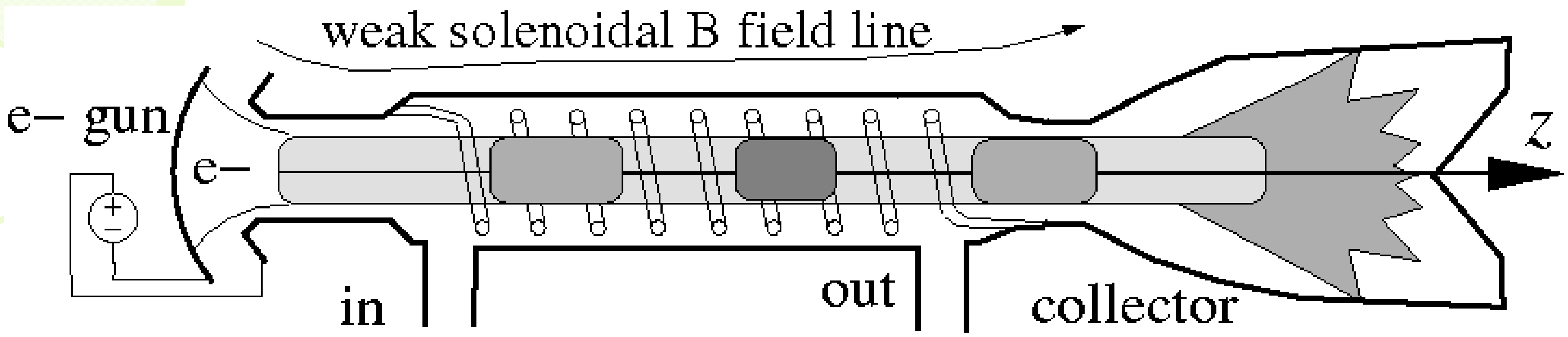


Figure 15: Trawelling wave tube (TWT)

Klystron have a very small bandwidth, since cavities are well separated and are typically excited in their fundamental mode

In a TWT, all cavities coalesce into one tube.

Moreover, to keep phase velocity $v_p=\omega/k_z$ of cavity waves near beam velocity u_0 (and thus well below c) this cavity is loaded by an helical electrode as in figure above.

Thus operation on large range of ω is possible (note that helix is designed so that k_z is about ω/ u_0 for this band, see [9])

4) GYROTRON and ECRIS (electron cyclotron resonance ion source).

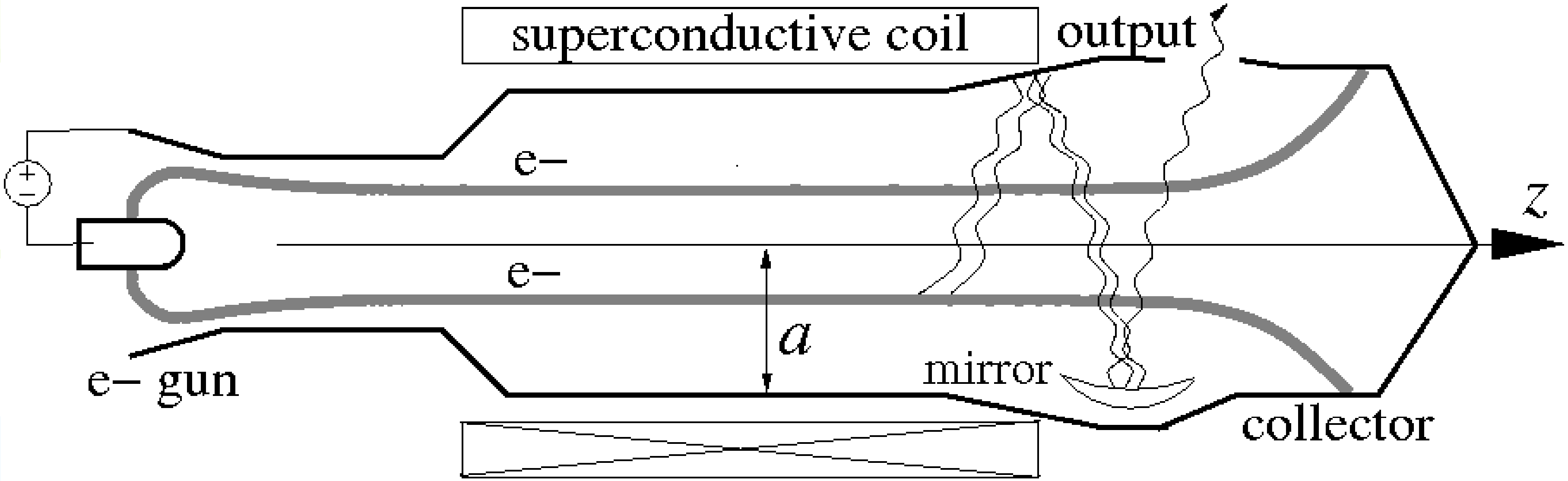


Figure 16: gyrotron concept scheme

A first difference of gyrotrons (with respect to klystrons) is the e-gun shape, conceived to impress to electrons a large magnetic moment, that is an helical motion spiraling around magnetic field lines: so at e-gun emitter E and B are crossed (in klystron e-gun E and B are roughly parallel to z). Spiraling motion has a so-called cyclotron angular frequency

$$\Omega_c = e|\mathbf{B}|/m\gamma$$

The magnetic moment is adiabatically conserved is static field. In other words, to lose magnetic moment electrons must interacts with rf fields

... gyrotrons

Since electrons have a considerable transverse velocity v_x, v_y comparable to v_z , they can couple efficiently also to TE and TEM modes of the cavity, which is a tapered tube. A small rf signal can synchronize the cyclotron oscillation of electron, that is to bunch electron in x,y,v_x,v_y phase space (a klystron bunches electrons in z, v_z phase space). By adequate design of magnetic field profile and tube radius, it can be obtained a bunch-to-rf phase adequate for rf emission (so cyclotron motion decelerates).

The same cyclotron resonance can be used to accelerate electrons in:

fusion plasma

ion source (where the magnetic field is also used to confine plasma, and is thus more complicate than in a gyrotron: an example of a 14 GHz ECRIS, using normal conducting coils and permanent magnets, is shown aside

ECRIS: SCHEME

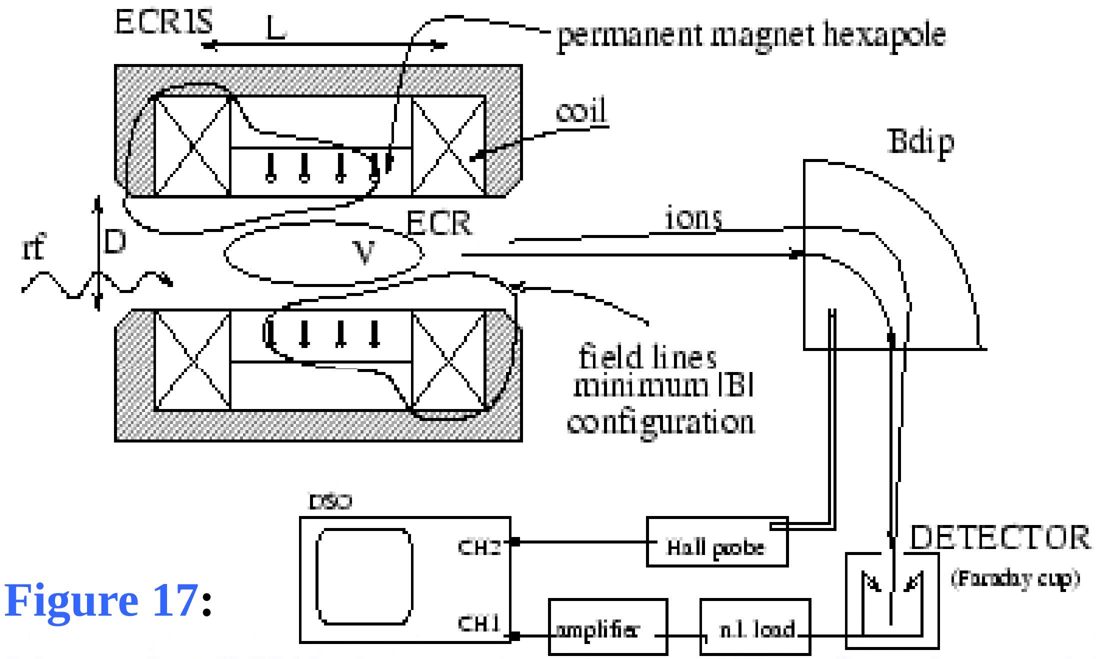


Figure 17: Scheme of an ECRIS: the central minimum of $|B|$ confines plasma, while microwaves heat electrons at the ECR surface; ions extracted are selected by a magnetic field dipole Bdip, detected at a faraday cup; data recorded by a digital sampling oscilloscope (DSO)

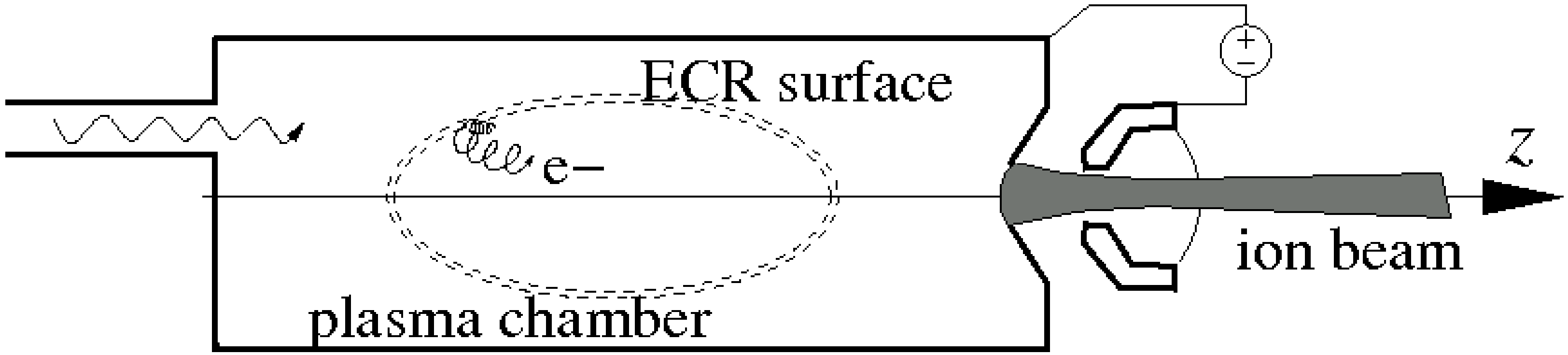


Figure 18: Scheme of an ECRIS (magnet not shown)

Pros of gyrotrons: (1) since λ may be much smaller than tube radius a , the tube power (of course increasing with a) is not limited by f $^{-2}$ scaling

(2) even if 95 GHz klystron development is reported, at millimetric wavelength, gyrotron cavity is much more robust (and 240 and 480 GHz gyrotrons are reported; 170 GHz are used in fusion plasma heating)

(3) millimetric waves can be transported by mirrors

Cons respect to klystron: (1) a superconducting magnet is needed for gyrotron performance

(2) efficiency is lower, since energy in z motion is not usable

(3) design seems more difficult

Cons respect to TWT: (1) for ECRIS, 18 GHz and few kW may be sufficient. Flexibility of TWT is often more requested

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Remarks and discussions

This review was focused to powerful rf generators (also multi Megawatts) in the sub-terahertz range, where the electron-gun based tubes (klystrons, TWT, gyrotrons) remains the standard solution; on the contrary for low power applications, solid state devices have now generally overcome small tubes, including triodes and reflex klystrons.

For the terahertz range (see next presentations) and above, electron-beam based devices emerged as standard (even if expensive) sources of powerful electromagnetic radiation, including the free electron lasers (FEL), the inverse Compton scattering and the synchrotron radiation.

Conclusion

The particle accelerator development motivates a progressive improvement of microwave generators, so that kinetic of electron bunching must be controlled and optimized, as discussed especially for klystron efficiency.

Both 1-D longitudinal dynamics and 3-D effects are important, as shown by new tuning concepts and by simulations, joining subjects of microwaves, plasma physics and particle accelerators.

Thank you for attention!