Free Electron Coherent Sources: CARM-U-FEL-C-FEL…

A Unified Point of view

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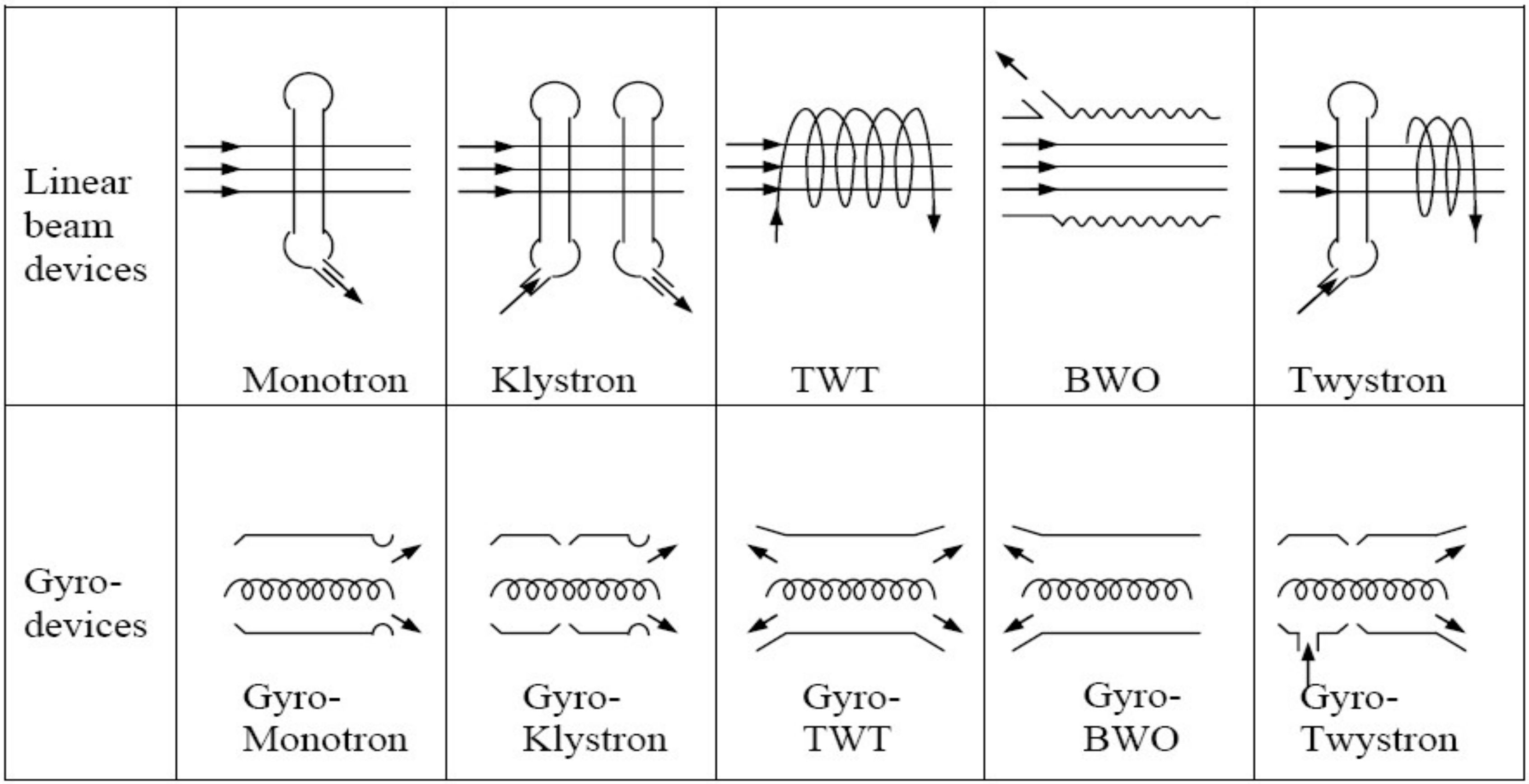
Topics to be covered

- Coherent Sources of Electromagnetic Radiation From «Free» Electrons
- A) Undulator based Free Electron Lasers
- B) Cerenkov, Smith Purcell…
- C) Coherent Autoresonance Maser (CARM), ENEA

Different RF Sources So Called HPM (High Power Microwaves)



What is a Free Electron Source?

A Tool to transform the kinetic energy of an electron beam into electromagnetic radiation with Laser-like properties

high intensity, small relative

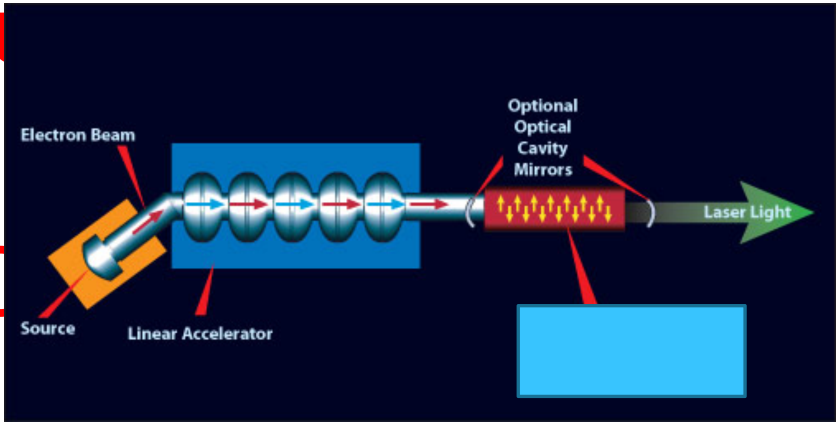
What are the basic elements of such a device?

A) An accelerator Capable of providing an e-beam with «suitable» characteristics

B) A device acting as active medi

C) operating

as «C

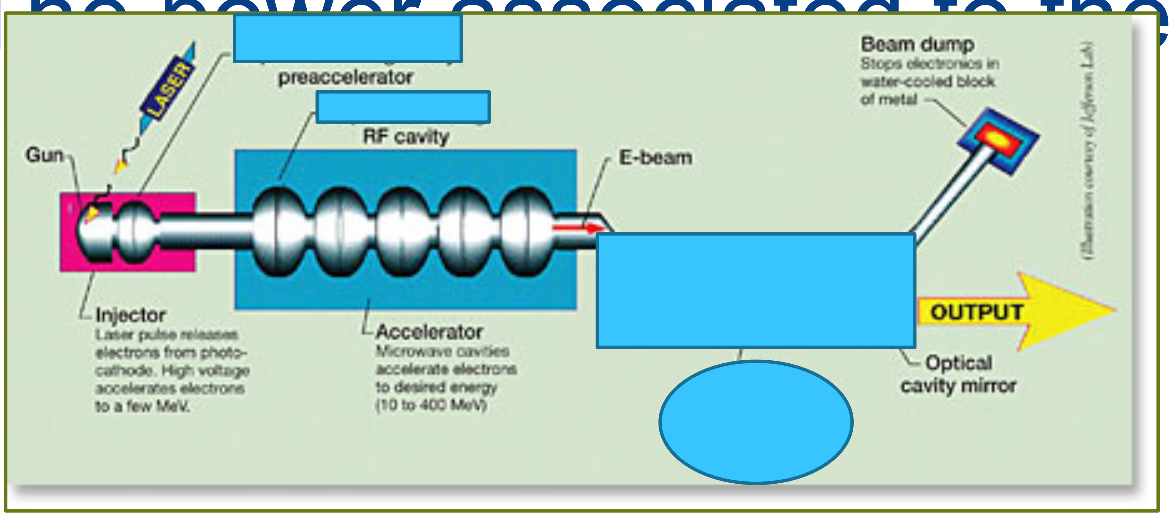


What is the Role of the accelerator?

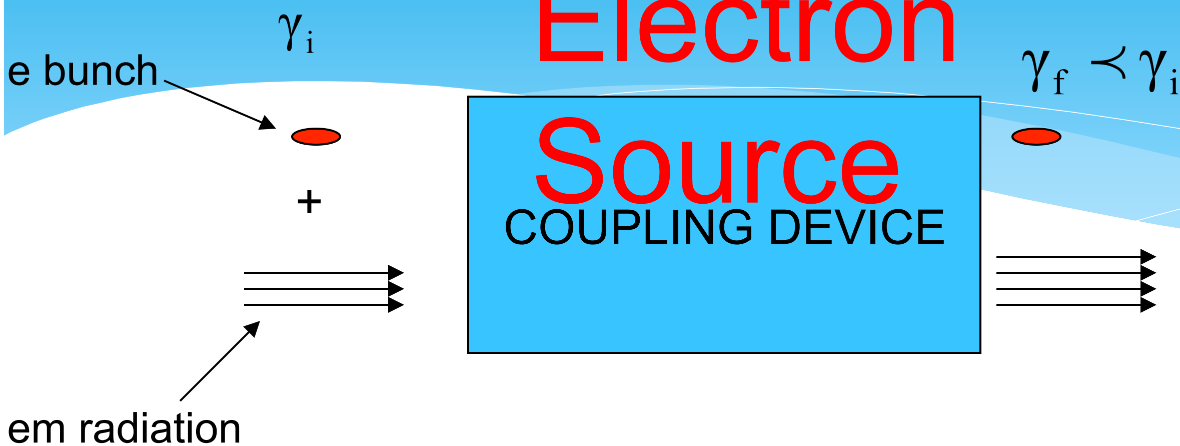
An RF Accelerating system brings to a relativistic Energy E an electron Beam of current I

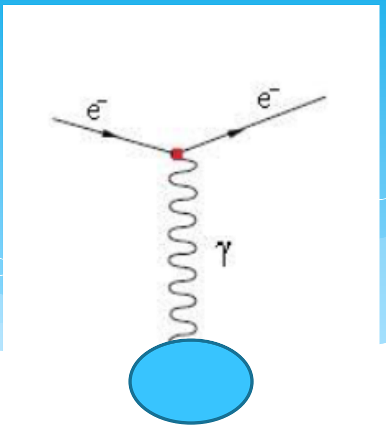
$$P_E[MW] = E[MeV]\,I[A]$$

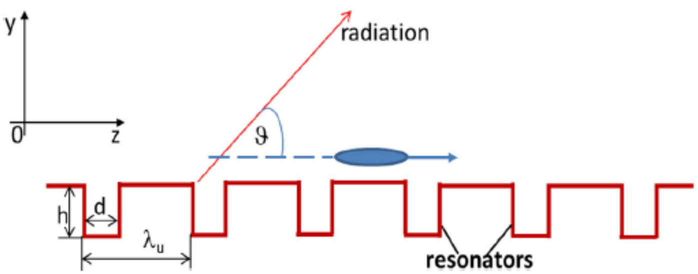
The power associated to the e-beam is

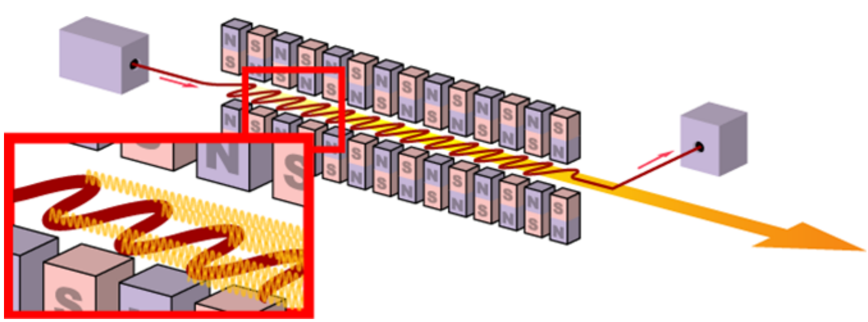


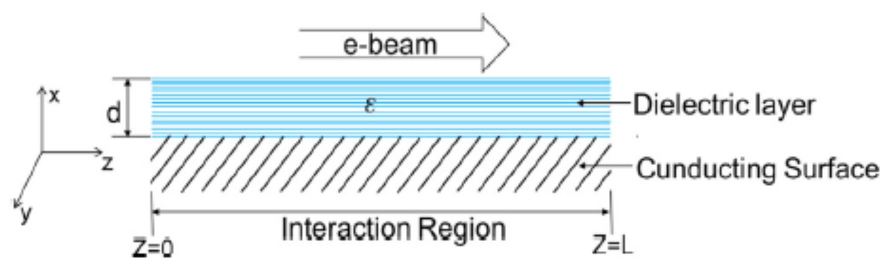
Free Electron Source

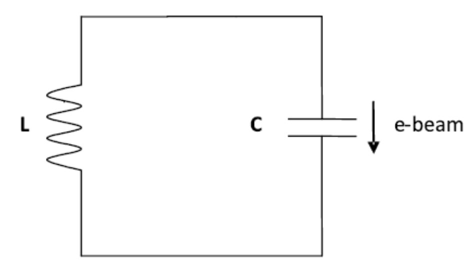








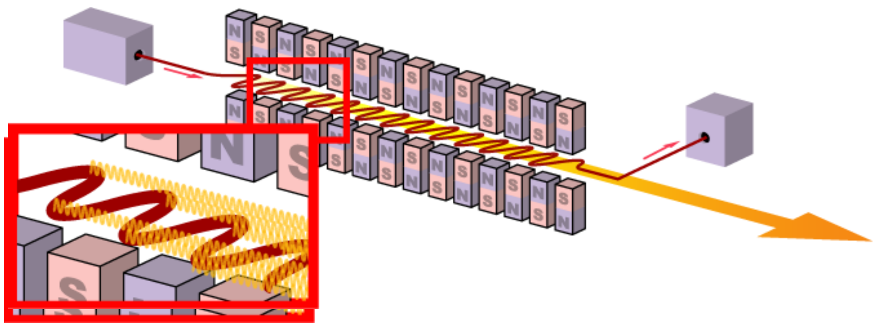




What is the role of the undulator in U-FEL?

$$\vec{B} = B_0(0, sin(\frac{2\pi z}{\lambda_u}), 0)$$

Induce a transverse oscillation via the Lorenz Force



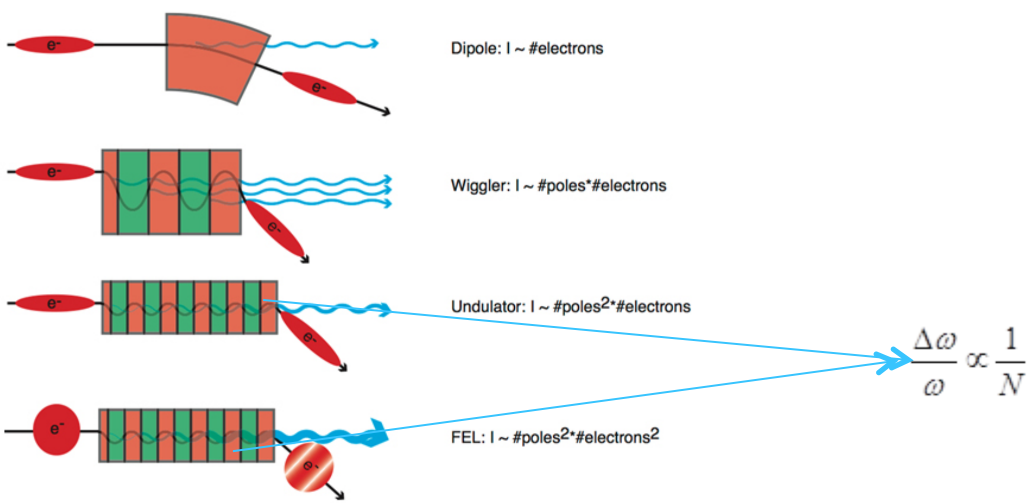
$$\lambda_u \equiv \text{undulator period},$$

$$L_u = N\,\lambda_u,$$

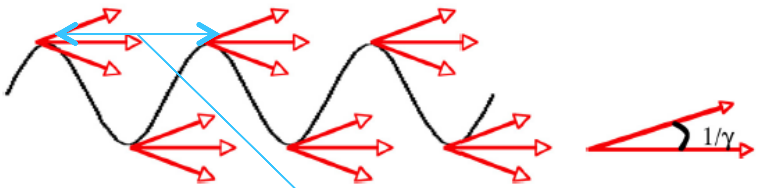
$$K \propto B_0 \lambda_u.$$

$$\beta_z^2 + \beta_\perp^2 = 1, \beta_\perp \cong \frac{1}{\sqrt{2}}\frac{K}{\gamma},$$

$$1 - \beta_z \cong \frac{1}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$



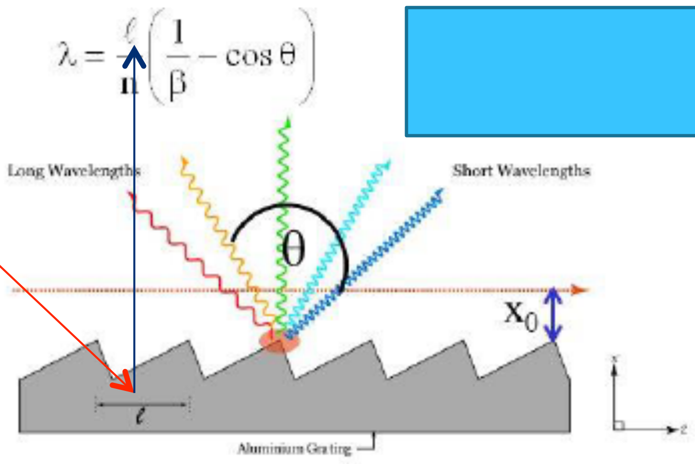
Wave-length selection



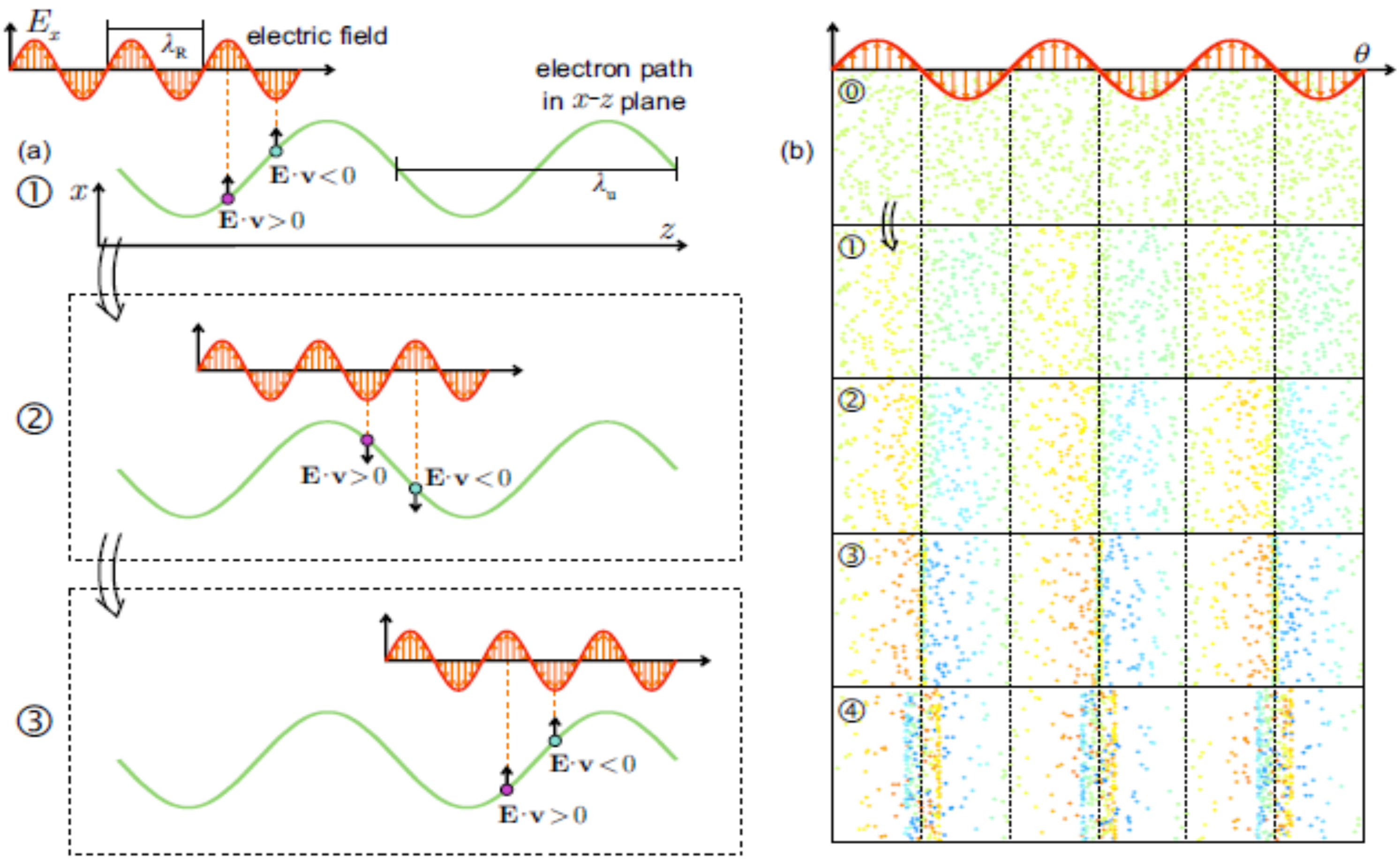
λ_u

$$\delta = (1-\beta_z)\,\lambda_u \rightarrow \lambda = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right),$$

$$\omega = \frac{2\gamma^2\,\omega_u}{\left(1+\frac{K^2}{2}\right)},\ \omega_u = \frac{2\pi c}{\lambda_u}$$



Energy-modulation-bunching-coherent emission-……



How Much Power can we steel from the electrons to Radiation?

FEL Efficiency

$$P_E = E\,I,$$

$$\frac{\Delta P_E}{P_E} = \frac{\Delta E}{E} = \frac{\Delta\gamma}{\gamma} = \frac{\gamma-\gamma_0}{\gamma_0}$$

$$P_L \cong \eta P_E$$

$$\eta_{U-FEL} \cong \frac{1}{4N}$$

Higher-Efficiency

$$P_E = E\,I,$$

$$\frac{\Delta P_E}{P_E} = \frac{\Delta E}{E} = \frac{\Delta \gamma}{\gamma} = \frac{\gamma - \gamma_0}{\gamma_0} \propto \frac{\Delta \omega}{\omega} \cong \frac{1}{4N},$$

$$P_L \cong \frac{1}{4N} P_E$$

$$\eta = \frac{1}{4N} \Rightarrow \eta_{FEL} >> \frac{1}{4N} ????$$

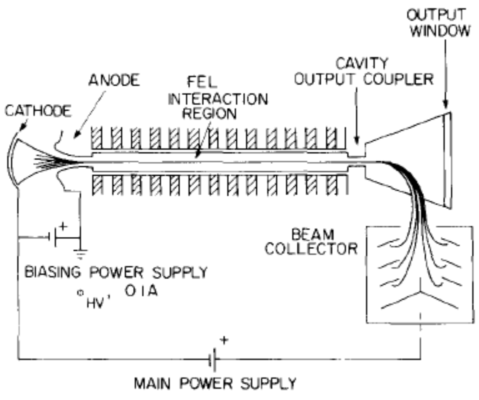
- Solution: Non Constant undulator parameters (TAPERING)

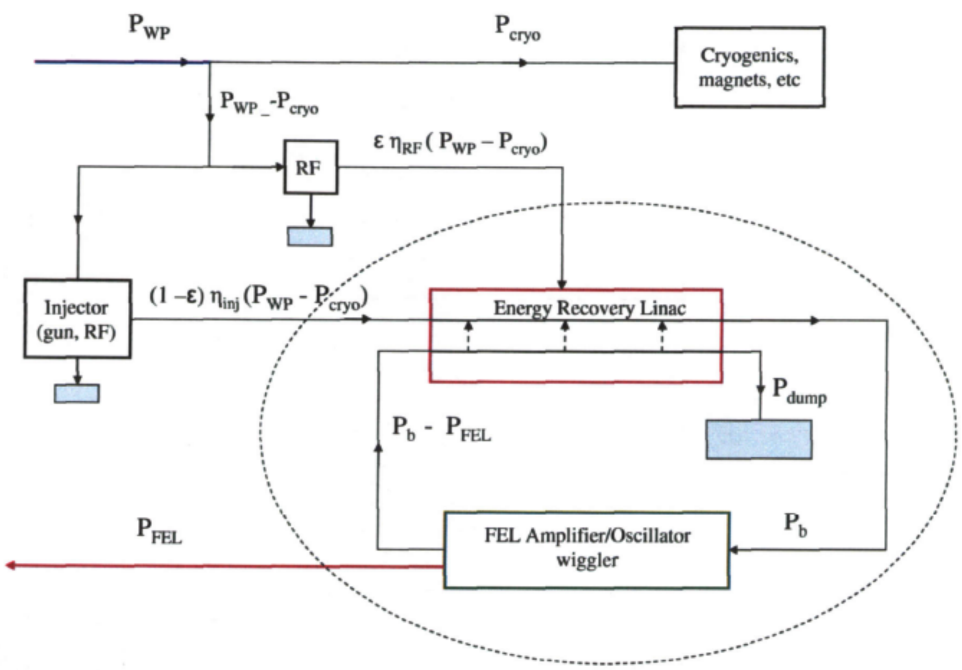
Energy recovery devices and Plug efficiency

- The beam is lost after any interaction, but can be recovered

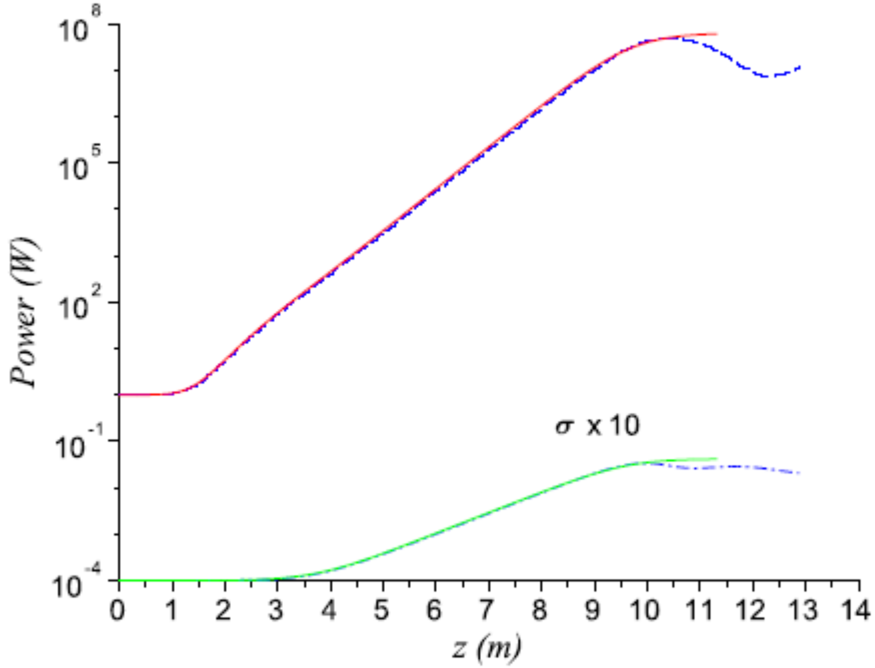
$$\eta_P = \frac{P_L}{P_P} = \frac{\eta\eta_{FEL}}{\eta_{FEL} + \frac{P_d}{P_E} + \eta\frac{P_{loss}}{P_E}},$$

$$\eta = \frac{P_E}{P_p - P_{loss}}$$





A Paradigmatic Behaviour



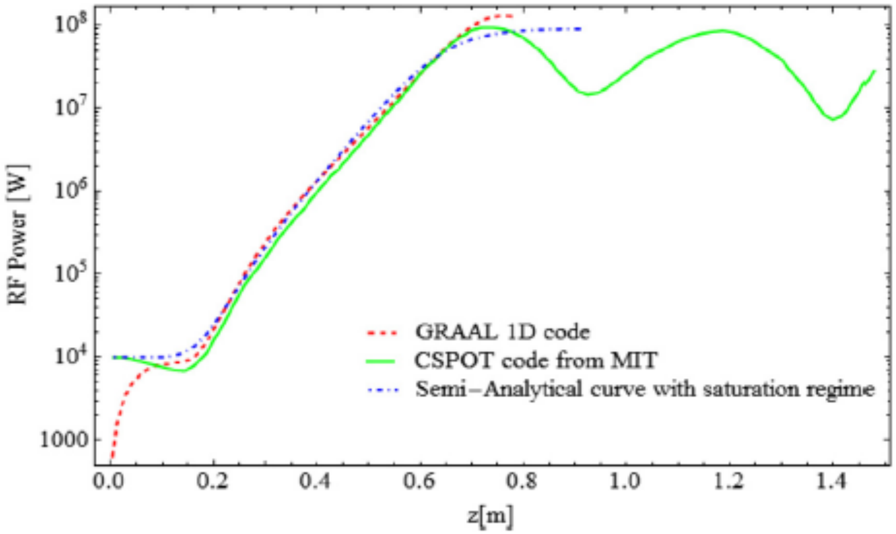
$$P(z) = P_0 \frac{A(z)}{1 + \frac{P_0}{P_F}\left[A(z) - 1\right]}$$

$$A(z) = \frac{1}{9}\left[3 + 2\cosh\left(\frac{z}{L_g}\right) + 4\cos\left(\frac{\sqrt{3}}{2}\frac{z}{L_g}\right)\cosh\left(\frac{z}{2L_g}\right)\right]$$

$$\sigma_i(z) \cong 3C\sqrt{\frac{A(z)}{1 + 9B\left[A(z) - 1\right]}}$$

$$C = \frac{1}{2}\sqrt{\frac{\rho P_0}{P_E}}, \qquad B \cong \frac{1.24}{9}\frac{P_0}{P_F}, \sigma_{i,F} \cong \frac{C}{\sqrt{B}} \cong 1.6\rho$$

CARM -POWER Growth Curve



$$\frac{d}{dz}P(z) = \frac{P(z)}{L_g}\left[1 - \frac{P(z)}{P_F}\right]$$

$$P_F = \sqrt{2}\rho\, P_E$$

$$P(z) = P_0 \frac{A(z)}{1 + \frac{P_0}{P_F}[A(z) - 1]}$$

$$A(z) = \frac{1}{9}\left[3 + 2\cosh\left(\frac{z}{L_g}\right) + 4\cos\left(\frac{\sqrt{3}}{2}\frac{z}{L_g}\right)\cosh\left(\frac{z}{2L_g}\right)\right]$$

$$\frac{da}{d\widetilde{z}} = i\int_0^{\widetilde{z}} (\widetilde{z} - \widetilde{z}')e^{-i\widetilde{\nu}_0(\widetilde{z}-\widetilde{z}')}a(\widetilde{z}')d\widetilde{z}',$$

$$\widetilde{z} = \frac{z}{L_g}, L_g = \frac{\lambda_u}{4\pi\sqrt{3}\rho}, \widetilde{\nu}_0 = \frac{1}{2\sqrt{3}\rho}\left(\frac{\omega - \omega_0}{\omega_0}\right)$$

$$\rho = \frac{1}{4\pi}\left(\frac{\pi g_0}{N^3}\right)^{\frac{1}{3}} = \frac{8.36\cdot 10^{-3}}{\gamma}\left[J(K f_b \lambda_u)^2\right]^{\frac{1}{3}}$$

C-FE-D –SCALING «formulae»

- *Just use*

$$\rho \cong \frac{8.36 \cdot 10^{-3}}{\gamma}\left(\mathrm{J}\left[\frac{\mathrm{A}}{\mathrm{m}^2}\right](\lambda_u\,[\mathrm{m}]\cdot K \cdot f_b(\xi))\right)^{\frac{1}{3}}$$

$$\rho_C = \frac{1}{4\pi}\left(\frac{32\pi^2}{I_0} J \gamma^3 \lambda^2\right)^{1/3}.$$

- *Get an idea of the importance of beam qualities*

$$\widetilde{\mu}_\varepsilon = \frac{2\sigma_\varepsilon}{\rho},$$

$$\widetilde{\mu}_\varepsilon << 1 \rightarrow \sigma_\varepsilon << \frac{\rho}{2}$$

Scaling Formulae

$$Z_F(\chi) = 1.066 L_g(\chi) \ln\left(\frac{9P_F(\chi)}{P_0}\right)$$

$$L_g(\chi) = \chi\, L_{g,1}$$

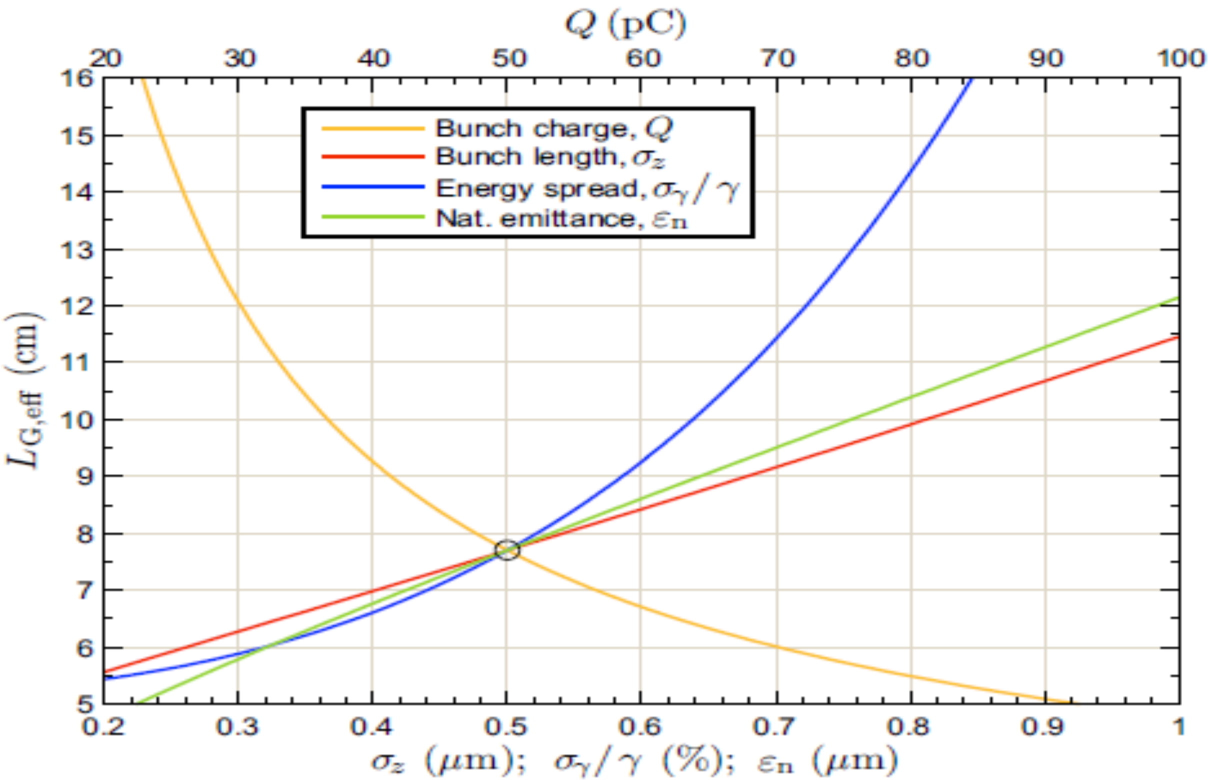
$$\chi = F_3^{-1}, \qquad F_3 = \frac{F_1}{F_2}\exp\left(c\widetilde{\mu}_\varepsilon^2\right)$$

$$F_1 = \frac{1 + a\left(\widetilde{\mu}_x^2 + \widetilde{\mu}_{x'}^2 + \widetilde{\mu}_y^2 + \widetilde{\mu}_{y'}^2\right) + b\left(\widetilde{\mu}_x + \widetilde{\mu}_{x'} + \widetilde{\mu}_y + \widetilde{\mu}_{y'}\right)}{\sqrt{\left(1+\widetilde{\mu}_x^2\right)\left(1+\widetilde{\mu}_{x'}^2\right)\left(1+\widetilde{\mu}_y^2\right)\left(1+\widetilde{\mu}_{y'}^2\right)}}, \qquad F_2 = 1 + dF_1\widetilde{\mu}_\varepsilon^2$$

$$a = 0.159,\ b = -0.066,\ c = -0.034,\ d = 0.185\frac{\sqrt{3}}{2}.$$

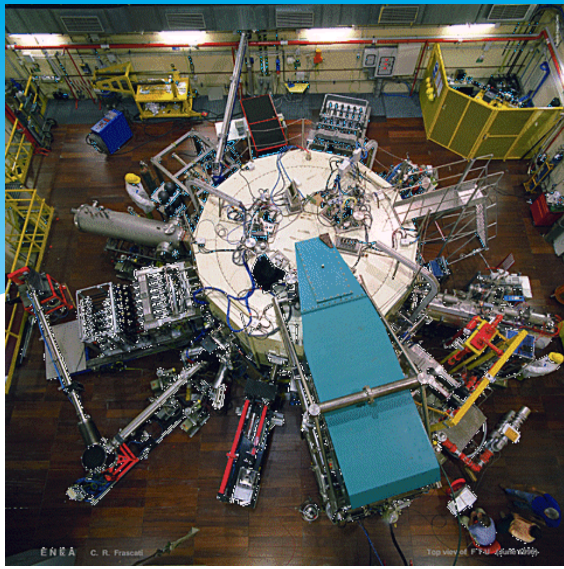
Scaling and optimization

Svetoslav Bajlekov
Merton College, Oxford



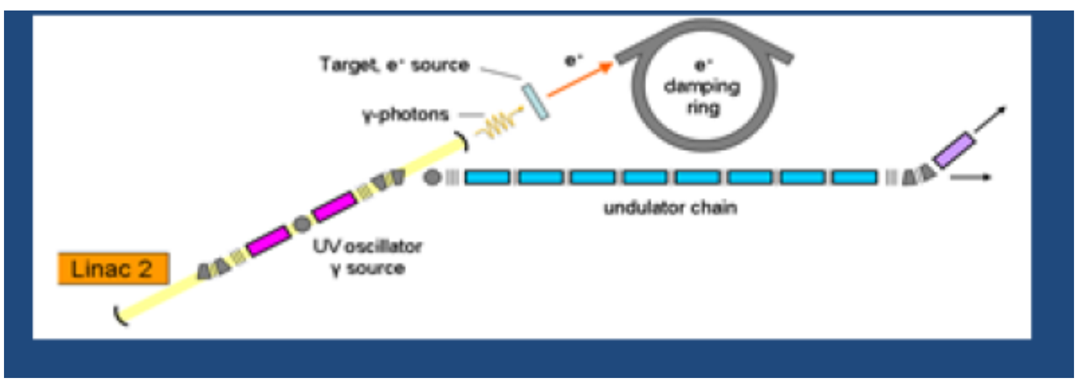
ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

What about FRASCATI LABS?

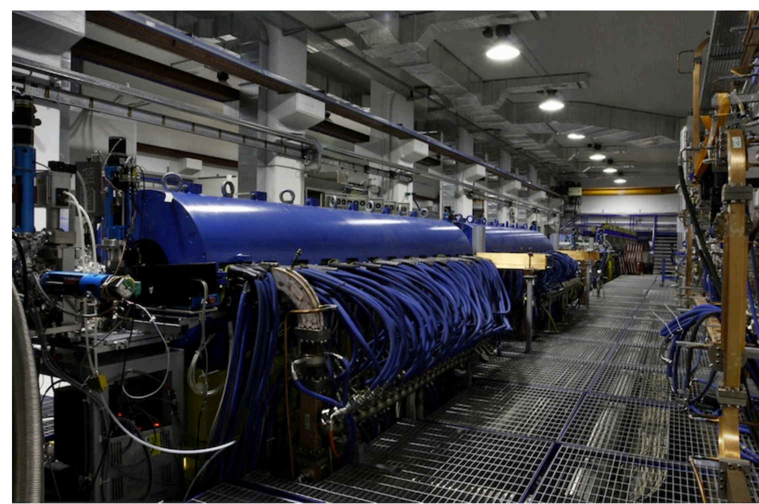


TOKAMAK

IRIDE



SPARC- Free-electron Laser

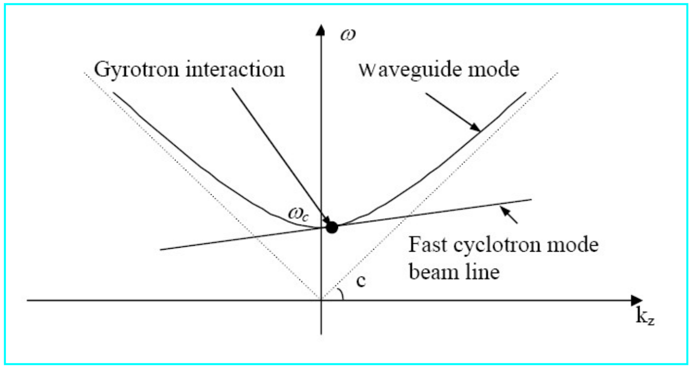


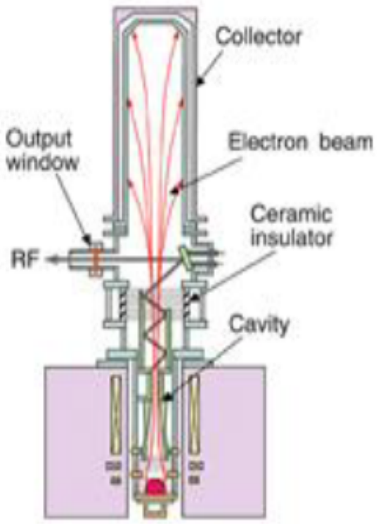
FE CS for fusion Plasma

Gyrotron

Current Principal Sources driven by low energy and high-current beam

– $\gamma \sim 1.05\text{-}1.1$; $I_b \sim 50\text{-}100A$





$$\omega_{rad} = s\Omega_c \equiv \frac{q_e B_0}{m_e \gamma}$$

…a significant present and an important future

From K. Sakamoto, Fusion Science and Technology, 2007

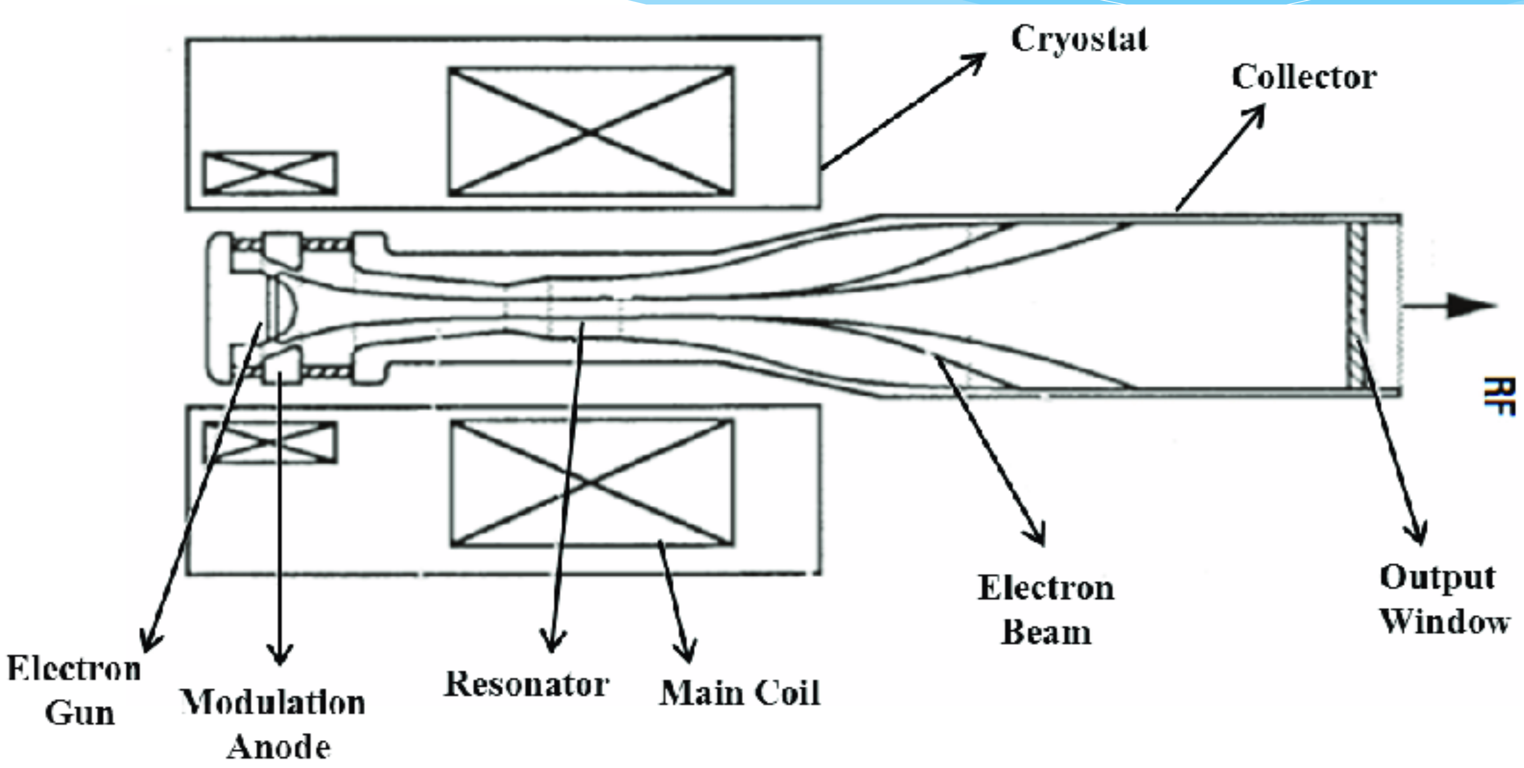
(a) Japan:$TE_{31,8}$ (b) Russia: $TE_{25,10}$ (c) EU: $TE_{34,19}$-coax

170 GHz gyrotrons for ITER

(a) US: $TE_{28,7}$-mode (b) EU: $TE_{28,8}$-mode

140 GHz gyrotrons for W7-X

Coherent Autoresonance maser



ENEA Frascati

CARM

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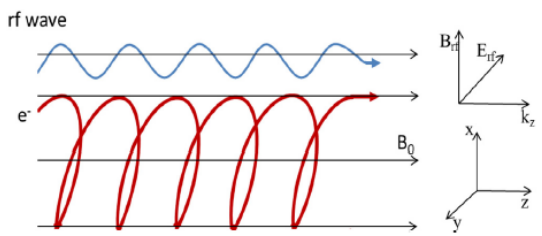

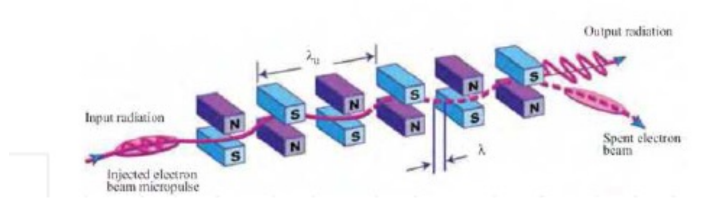

$$\Omega = \frac{e\,B}{m_e \gamma}$$

$$\Lambda = \frac{c}{\Omega} \rightarrow \lambda_u$$

$$\beta_z = \sqrt{1 - \frac{1}{\gamma_z^2}},$$

$$\gamma_z = \frac{\gamma}{\sqrt{1+\alpha^2}},$$

$$\alpha \rightarrow K$$

$$\gamma = \frac{1}{\sqrt{1 - \beta_z^2 (1+\alpha^2)}},$$

$$\beta_z = \frac{v_z}{c}, \alpha = \frac{v_\perp}{v_z}$$

$$(v_p - v_z)\frac{\Lambda}{c} = \lambda,$$

$$v_p = \frac{\omega}{k_z}$$

$$\omega = \Omega + k_z v_z$$

An other FEL conception

CARM a Bridge between Gyrotrons and conventional FELs

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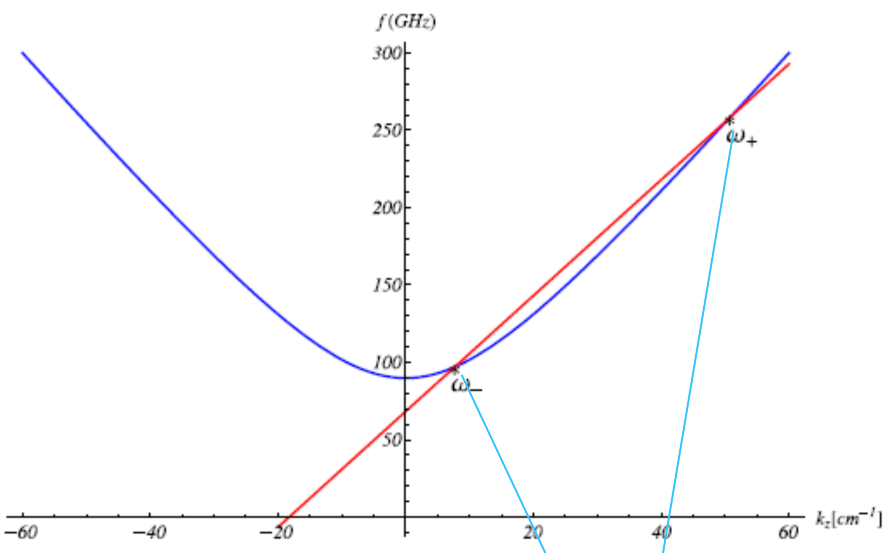
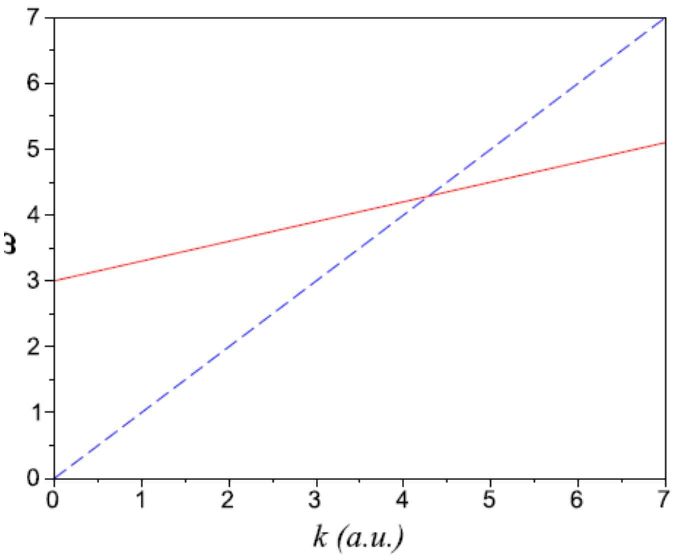


$$\omega^2 = c^2(k_\perp^2 + k_z^2)$$

$$\omega_- \cong \frac{\Omega}{1+\beta_z} \equiv \text{Gyrotron frequency.}$$

$$\omega = \frac{\Omega_0}{\gamma} + k_z c \beta_z .$$

$$\omega_+ \cong \frac{\Omega}{1-\beta_z} \equiv \text{CARM frequency,}$$



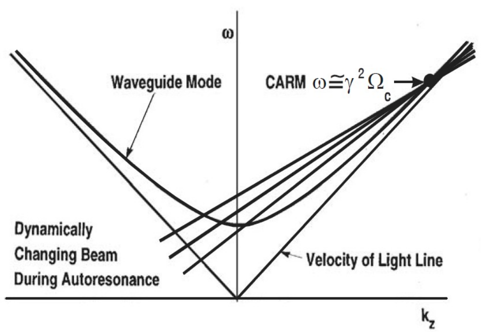
Power From the e-beam: The same Paradigm

- Electron Power to Radiation Field (the intrinsic efficiency is larger...)

$$P_{CRM}[MW] = \hat{\eta}\, I[A]V[MV]$$

$$\Lambda = \frac{c}{\Omega} \rightarrow \lambda_u \rightarrow \frac{mc^2\gamma}{eB}$$

- Naturally TAPERED device



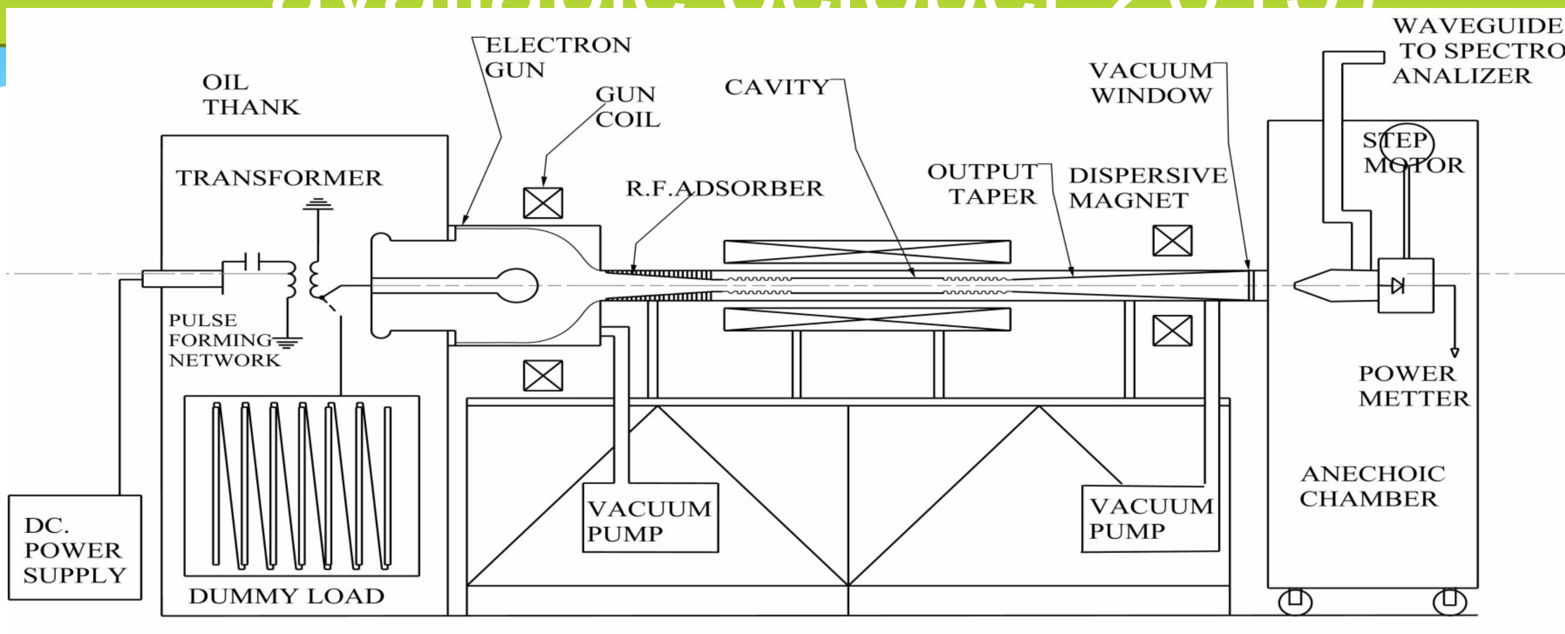
Derivation of the operating parameter for CARM operation at 250 GHz

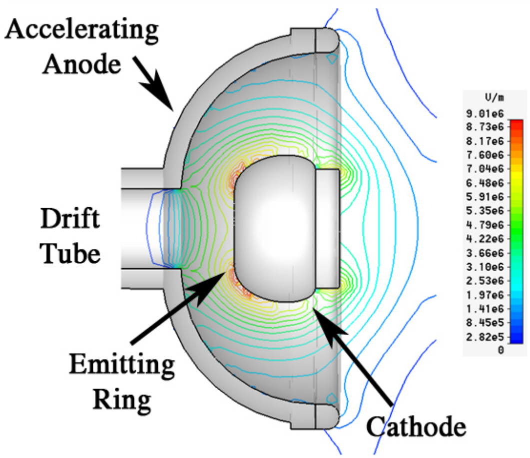
* A) Frequency $\omega_s \cong \dfrac{\Omega}{\left(1-\dfrac{\beta_z}{\beta_p}\right)}$ $\gamma_0 \cong 2.2 \to 0.7MV,$ $B = 5T$

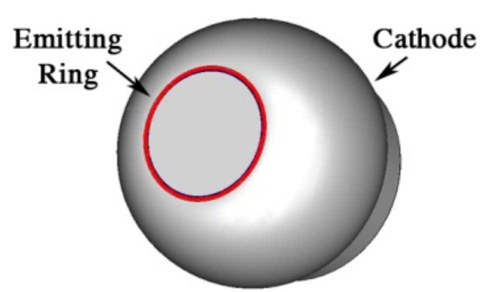
B) Power (CARM) 1,2 MW

$$P_{CRM}[MW] = \hat{\eta}\, I[A]V[MV] \qquad \hat{\eta} \cong 0.35 \quad I = 5\ A$$

Preliminary design elements (TDR available october 2015)



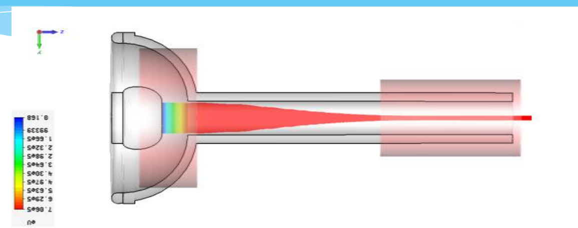


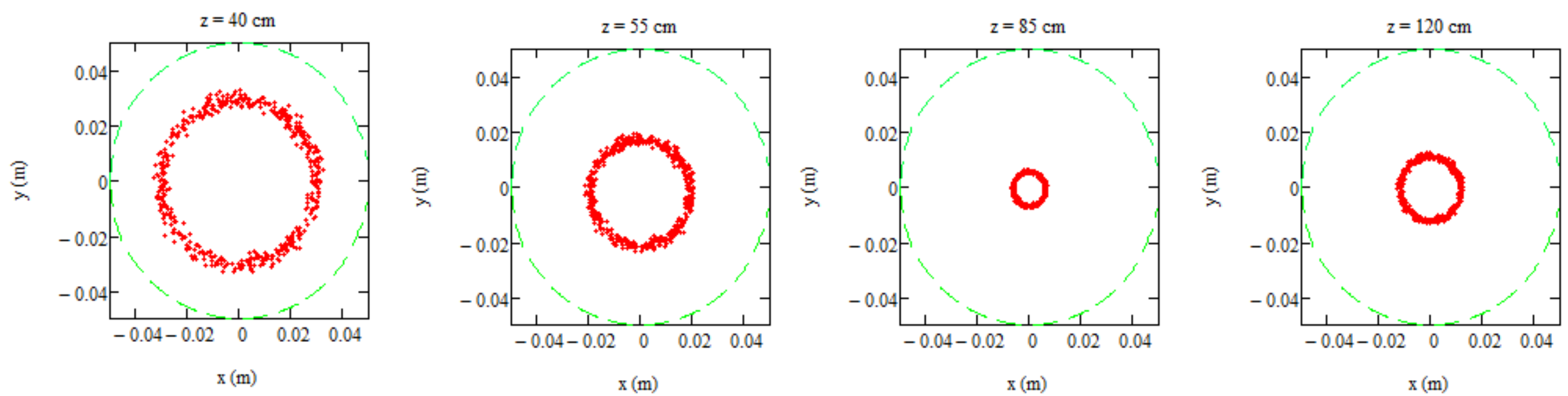


$$\beta_z = \frac{1}{\gamma_0}\sqrt{\frac{\gamma_0^2 - 1}{1+\alpha^2}},$$

$$\gamma_0 = \frac{|e|V}{m_e c^2} + 1$$

Start to End Electron Beam Simulation





Courtesy of F. Ciocci, Ivan Spassovsky & Emanuele Di Palma

Electron Cyclotron Resonance Heating- ECRH

- ECRH is important for advanced TOKAMAK research
- Effective source of highly localized and controlled heating and current drive
- Coupling of power to the wave is easy
- Power density can be very high (~10^9 W/m2)
- Pinpoint localization of EC power support stabilization of MHD
- ITER needs 25 MW at CW operation

Potential Advantages

i) high efficiency due to “auto-resonant” compensation

ii) comparable efficiency with gyrotrons and more stable against the excitation of parasitic modes

iii) operation far from cutoff should reduce fields at cavity walls

iv) operation at lower values of magnetic field.

Dedicated To Amalia Torre
(1957-2018)
A Distinguished Member of ENEA theory Group