Free Electron Lasers :

The Challenge EUPRAXIA

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ENEA FRASCATI

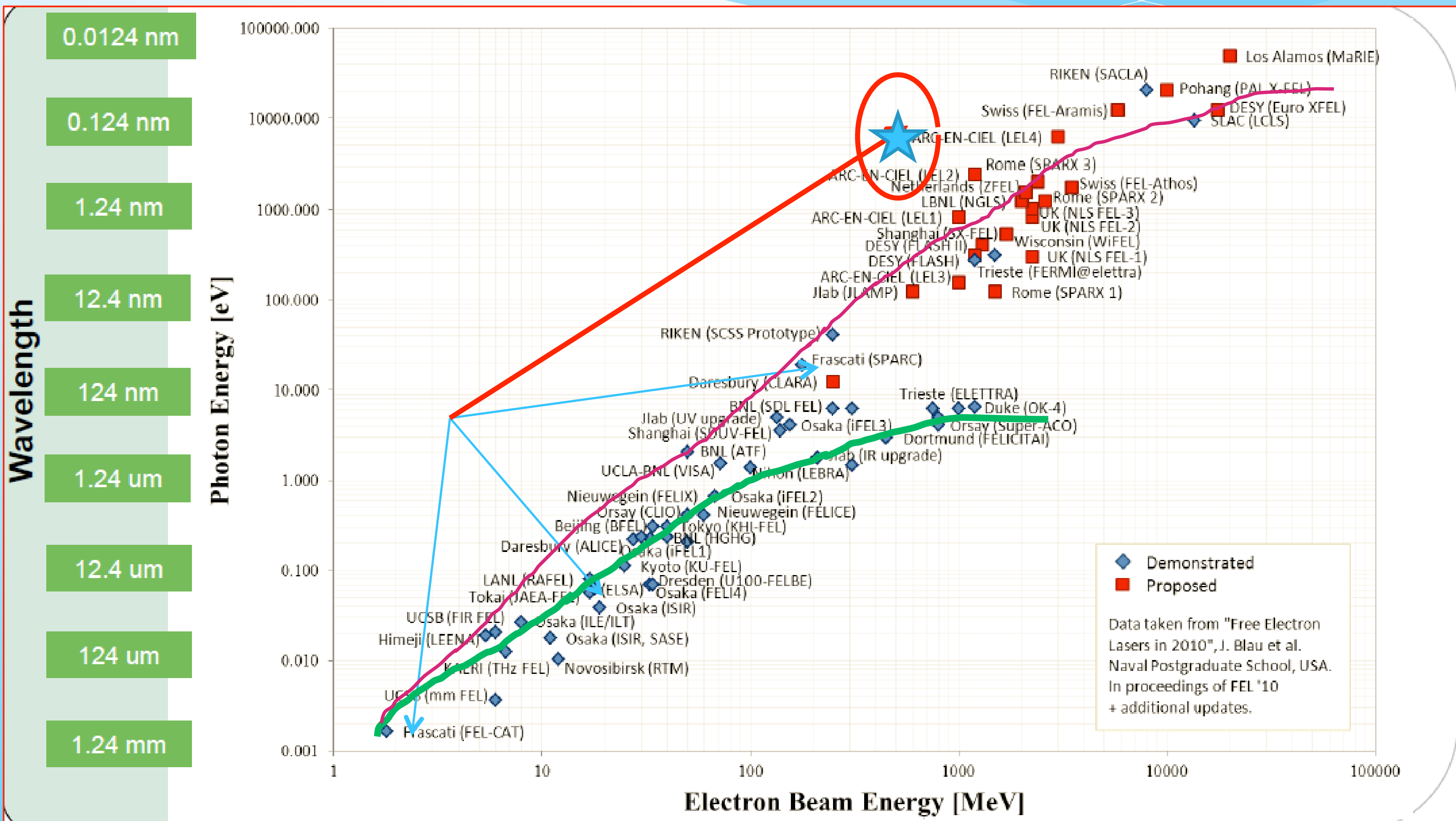
Fusion Department

Energy and frequency

Letardi - Chart

$$\lambda \cong \frac{1}{2\gamma^2}\left(1+\frac{K^2}{2}+(\gamma\vartheta)^2\right)\lambda_u$$

$$\omega \cong \frac{2\gamma^2}{1+\frac{K^2}{2}+(\gamma\vartheta)^2}\,\omega_u$$

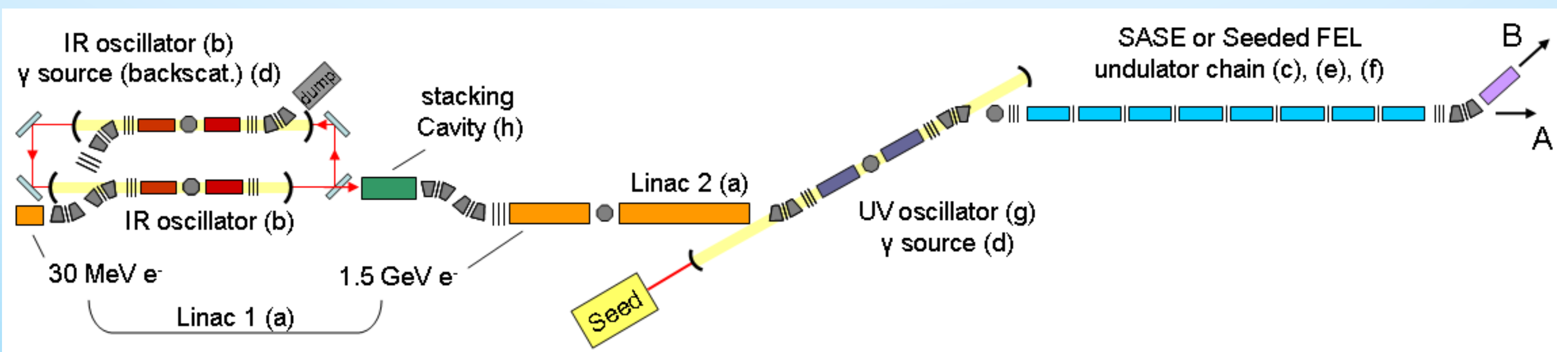


What about money?

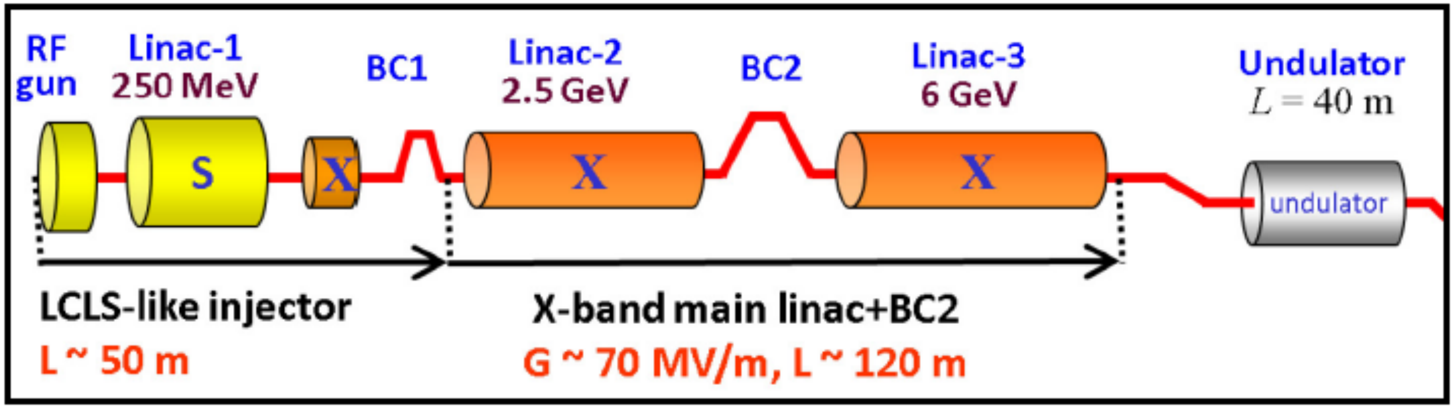
FEL size and cost

Wavelength	Energy	Size [m]	Cost [M$]
IR 2-10 μm	10-40 MeV	3-10	1-5
EUV 13.5 nm	0.5-1 GeV	40	30-50
X 0.15 nm	15 GeV	500-1000	1000

IRIDE *(Future???)*



An exercise: X-Band LINAC (70 MeV/m)



SLAC-PUB-14276

Chris Adolphsen, Zhirong Huang, Karl L.F. Bane, Zenghai Li, Feng Zhou, Faya Wang, and Christopher D. Nantista

Parameter	symbol	*LCLS*	X-band FEL	unit
Bunch Charge	Q	250	250	pC
Electron Energy	E	14	6	GeV
Emittance	$\gamma\varepsilon_{x,y}$	0.4-0.6	0.4-0.5	μm
Peak Current	I_{pk}	3.0	3.0	kA
Energy Spread	σ_E/E	0.01	0.02	%
Undulator Period	λ_u	3	1.5	cm
Und. Parameter	K	3.5	1.9	
Mean Und. Beta	$\langle\beta\rangle$	30	8	m
FEL wavelength	λ_r	1.5	1.5	Å
Sat. Length	L_{sat}	60	30	m
Sat. Power	P_{sat}	30	10	GW
FWHM Pulse Length	ΔT	80	80	fs
Photons/Pulse	N_γ	2	0.7	10^{12}

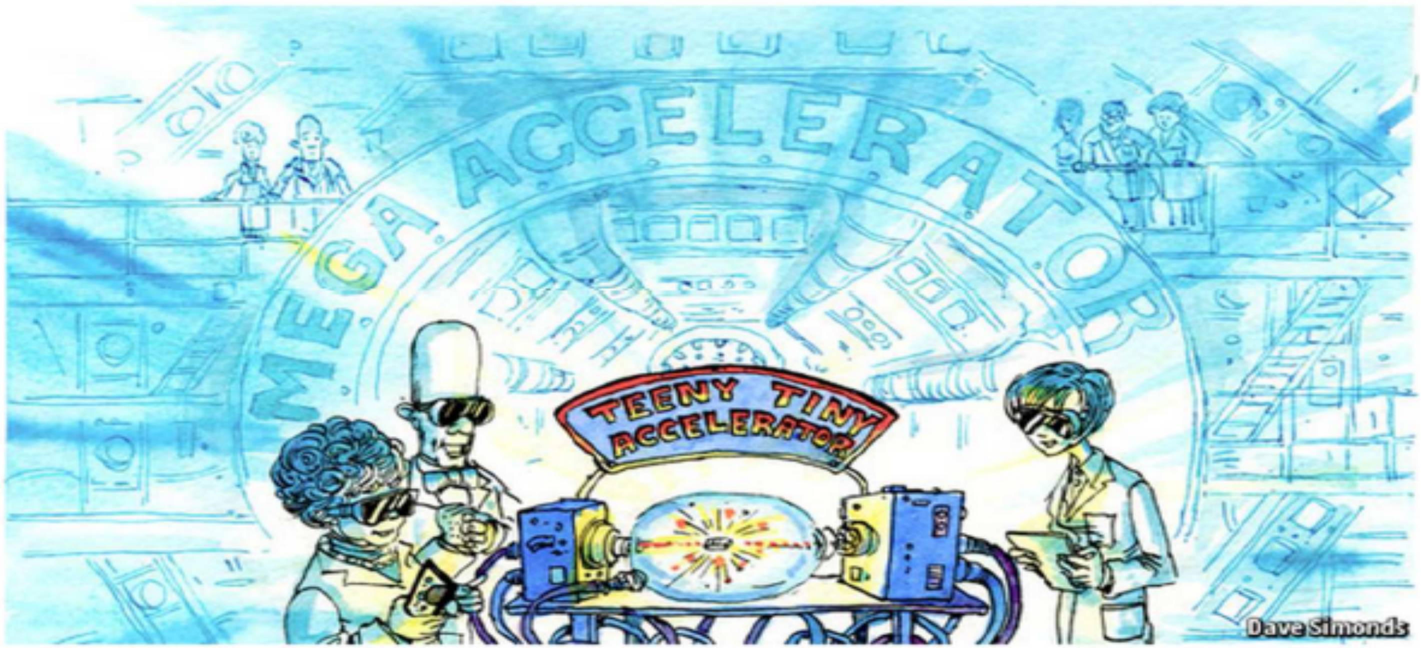
The Challenges

* A) Reduce the costs
* B) reduce the sizes
* C) Improve the «light» coherence properties
* D) Increase the number of experimental stations
*

Reduce cost and size:The problem is of public domain

Fundamental physics seems to have an insatiable appetite for bigger, more expensive machines. There may, though, be a way to shrink them radically

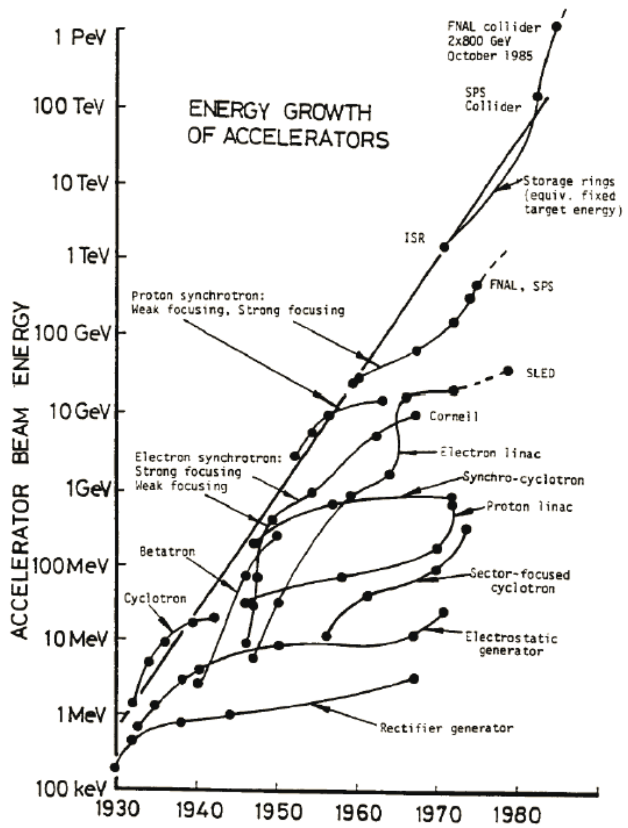
Oct 19th 2013 | From the print edition

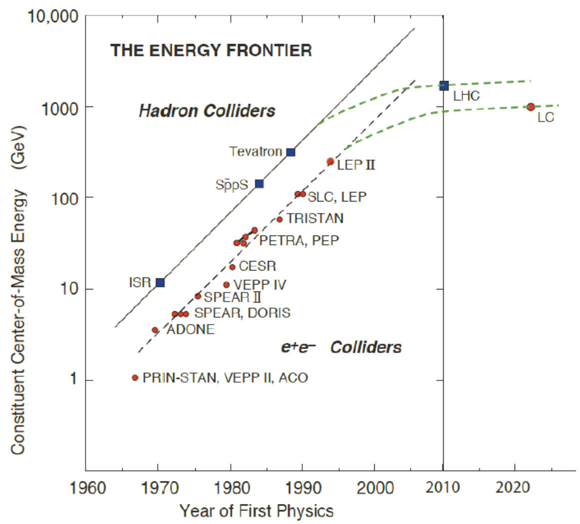


BIG science tends to get bigger with time. The first modern particle accelerator, Ernest Lawrence's cyclotron, was 10cm across and thus fitted comfortably on a benchtop. It cost (admittedly at 1932 prices) $25. Its latest successor, the Large Hadron Collider (LHC), has a diameter of 8.6km (5.3 miles) and does not even fit in one country: it straddles the border between France and Switzerland, near Geneva. It cost $5 billion. Clearly, this is a trend that

Cannot continue for longer time

Livingston Plot and Saturation of technologies

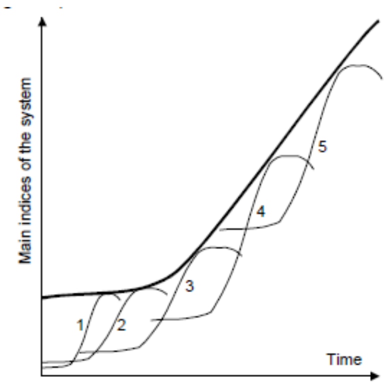




Livingston Chart 2010

Progress has slowed in pushing the energy frontier

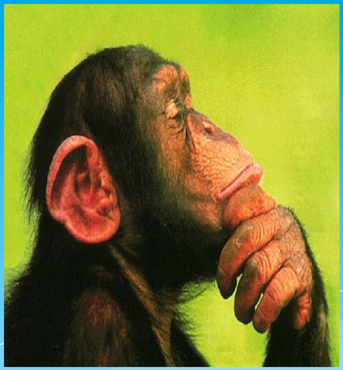
No longer proceeding along at the rate of development seen over the previous 60 years



. Successive substitutions of new systems for old ones following the law of Ideality growth.

Think!!!

It might be a new experience!!!



What's wrong with the status quo?

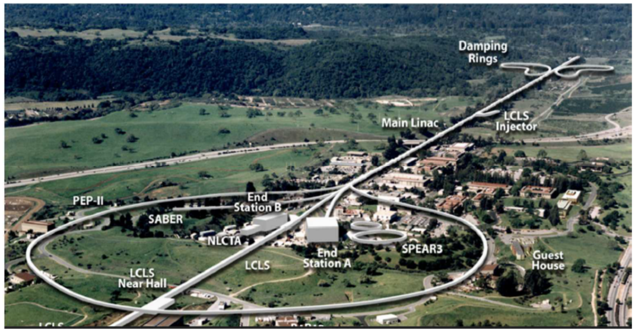
- Existing facilities are large, this means:
  - High-cost ➔Limited access
  - Limited access ➔Risk to science
    - Pressure to publish in every experiment
    - Beam time precious; hard to *verify* experiments by other teams
  - Result: Pace of science is slowed, quality may be compromised.

***5th Generation Light Source*:**

Re-invent XFEL to fit in campus laboratory

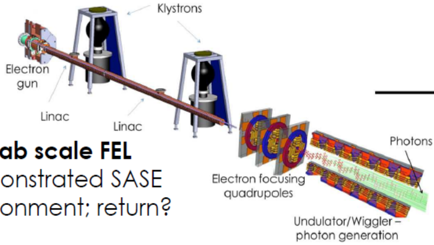
3

The X-ray FEL is enormous. Challenge is to fit this…



1 km

Into this…

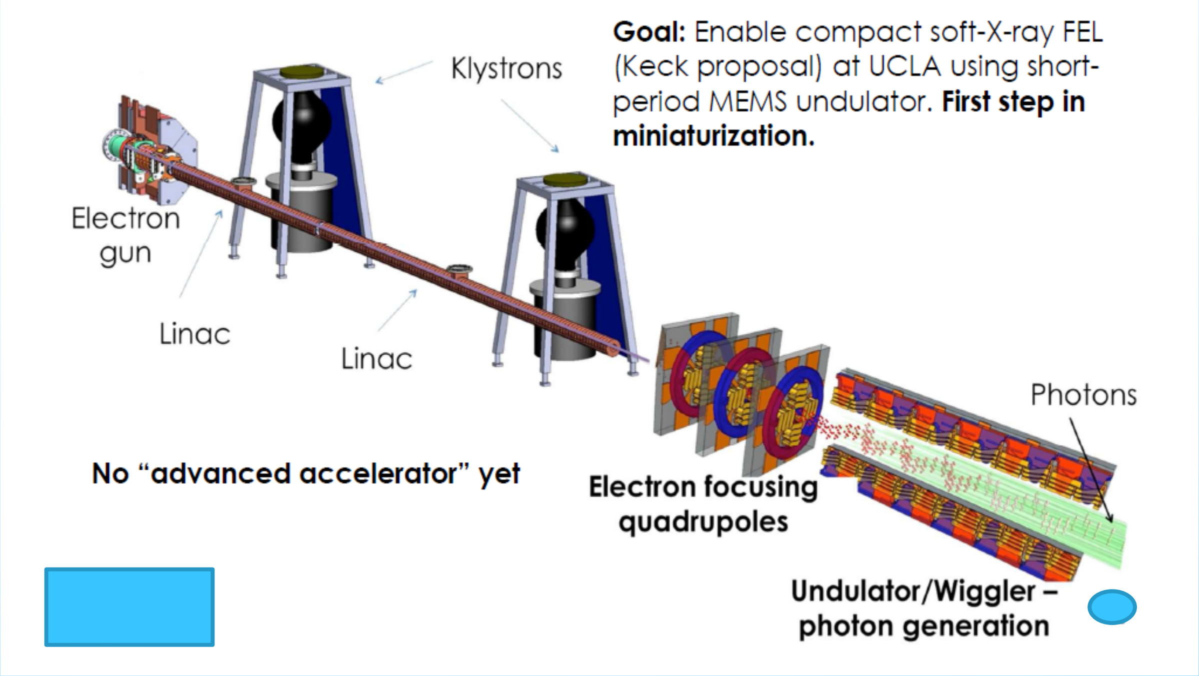


5 m

The university lab scale FEL
UCLA first demonstrated SASE FEL in this environment; return?

2

Towards «Bonsai» FEL

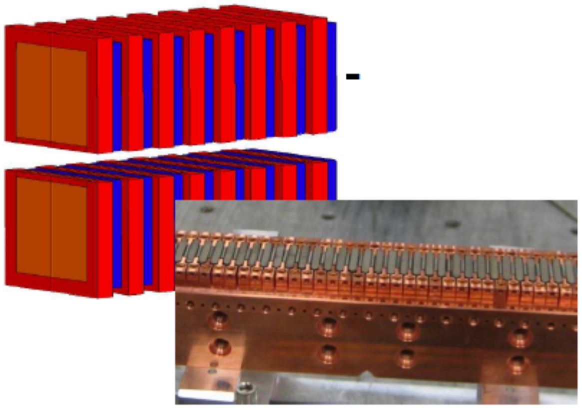


ELEMENTS FOR A STRATEGY

* A) Reduce the undulator length using exotic devices
* (Laser Wave undulators, R.F. Undulators,….)
* B) Reduce the size of the accelerator using different

Courtesy of J. Rosenzweig

What's next: the 5th generation ultra-com…

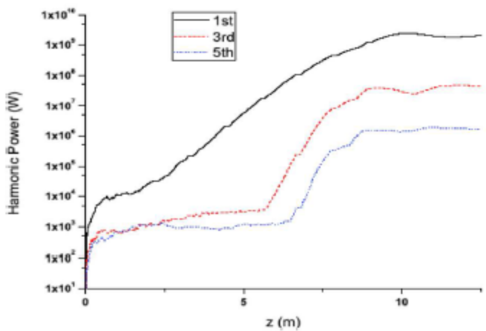


- **High brightness beam (HBB)**
  - low charge (pC), ultrashort pulses
  - Ultralow emittance

J.B. Rosenzweig, et al., *Nucl. Instruments Methods A*, 593, 39 (2008)

- **High field, short ⌊ undulator**
  - With HBB, large ⟩, short L_g
- **Lowers e- energy needed** to reach short wavelength
  - *Ex: 2 GeV* hard X-ray FEL
  - ***Much smaller accelerator, undulator***
- **Utilize *high gradient* accelerators to shrink the FEL dramatically**

Hybrid cryo-undulator: Pr-based, SmCo sheath; ⌊ =9 mm up to 2.2 T



F.H. O'Shea et al, PRSTAB 13, 070702 (2010)

FEL w/1 pC driver at 2.1 GeV

Pathway to a Compact SASE FEL Device

G. Dattoli,[1] E. Di Palma,[1] V. Petrillo,[2] J.V. Rau,[3] E. Sabia,[1]
I. Spassovsky,[1] S.G. Biedron,[4] J. Einstein,[4] and S.V. Milton[4]

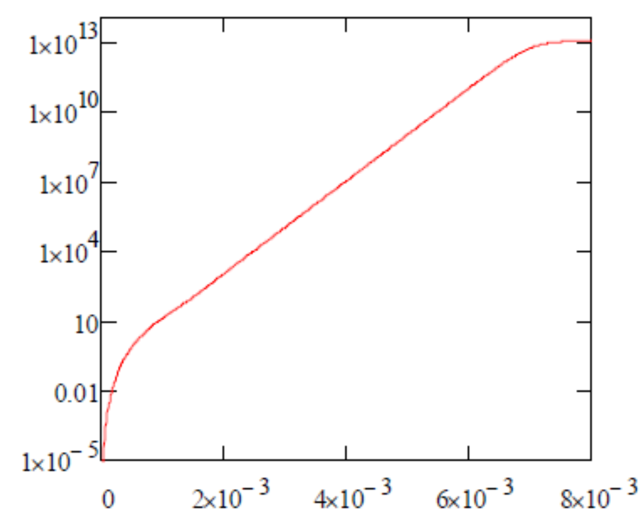
[1] *ENEA - Centro Ricerche Frascati, Via Enrico Fermi 45, 00044, Frascati, Rome, Italy**
[2] *Università degli Studi di Milano, via Celoria 16, 20133 Milano, Italy*
[3] *Istituto di Struttura della Materia, ISM-CNR, Via del Fosso del Cavaliere, 100-00133 Rome, Italy*
[4] *Colorado State University*

* Wave undulators: Use a laser instead of a magnetic device

The State of the art: ATF experiment

M. N. Polyanskiy, I. V. Pogorelsky and V. Yakimenko
Optics Express 7717, Vol. 19, April 11 (2011)
V. Yakimenko, CO_2 Laser Based undulator for a compact SASE FEL
Talk delivered at "Laser and Plasma Accelerators Workshop 2011"
Brookhaven (New Jork) June 20-21 (2011)

Electron beam	
E[Mev]	77.3
I[A]	$1.5\cdot10^3$
$\frac{E}{E_x}\rho$, $E_x[keV]=\hbar\omega_s$	8.6 10
Laser Energy [J]	30
Laser duration [ps]	30



Plasma accelerating schemes

In underdense plasma an ultraintense laser pulse excites a large-amplitude plasma wave with frequency

$$\omega_p = \sqrt{\frac{4\pi e^2 n_p}{m}} \tag{1}$$

and electric field of the order of

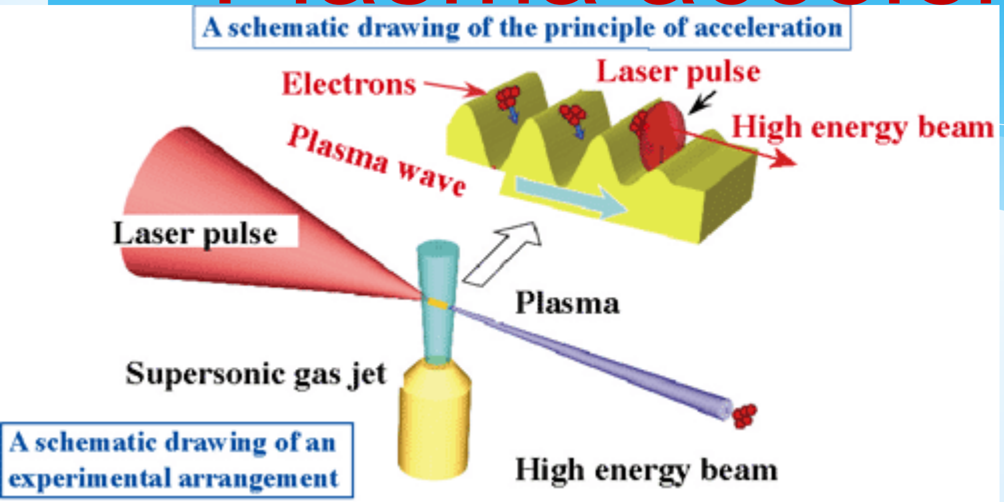
$$E_0 = \frac{mc\omega_p}{e} \simeq 96\left[\mathrm{GV/m}\right]\sqrt{\frac{n_p}{10^{18}\left[\mathrm{cm}^{-3}\right]}} \tag{2}$$

for the electron rest energy mc^2 and plasma density n_p due to the ponderomotive force expelling plasma electrons out of the laser pulse and the space charge force of immovable plasma ions restoring expelled electrons on the back of the ion column remaining behind the laser pulse. Since the phase velocity of the plasma wave is approximately equal to the group velocity of the laser pulse

$$\frac{v_p}{c} \simeq \sqrt{1-\frac{\omega_p^2}{\omega_L^2}} \sim 1 \tag{3}$$

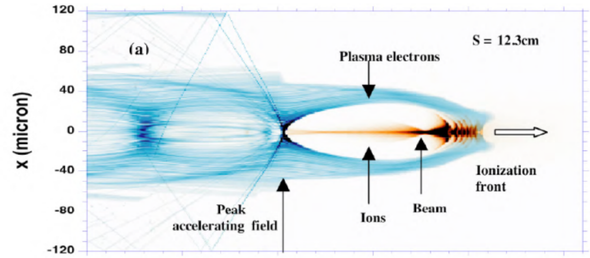
for the laser frequency ω_L and the accelerating field of ~ 100 GV/m for the plasma density ~ 10^{18} cm^{-3}, electrons trapped into the plasma wave are likely to be accelerated up to ~ 1 GeV energy in a 1-cm plasma.

Plasma accelerating scheme



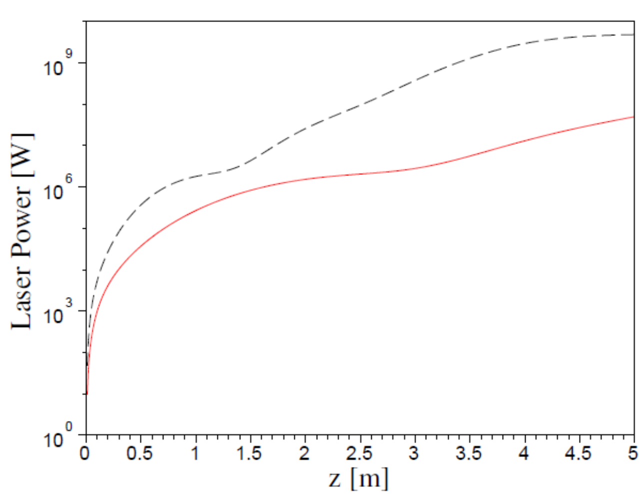
Plasma Wakes – Theory

- Above this limit: non-linear wakes, “Blow-out regime”
- Fields can be calculated only with numerical methods

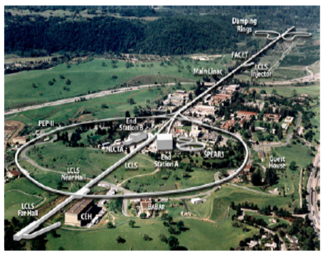


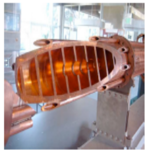
- Typical wavelength: 50 μm
- Accelerating fields up to 50 GV/m

Undulator parameter	$K = 2$
Undulator period	$\lambda_u = 1cm$
Beam energy	$E = 1GeV$
Resonant wavelength	$\lambda \approx 1nm$
Peak current	$I \approx 10kA$
Energy spread	$\sigma_\epsilon \approx 10^{-2}$
Normalized emittances	$\gamma\epsilon_{x,y} \approx 1\mu mrad$
Horizontal and vertical size	$\sigma_{x,y} \approx 11.3\mu m$
FEL parameter	$\rho \approx 6 \cdot 10^{-3}$

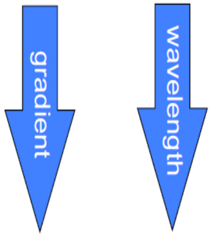


Is the future coming?



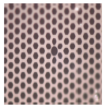


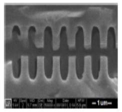
30 MV/m λ = 10 cm

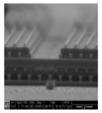


x10^{-4}

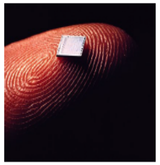
1-2 GV/m λ = 1-10 µm





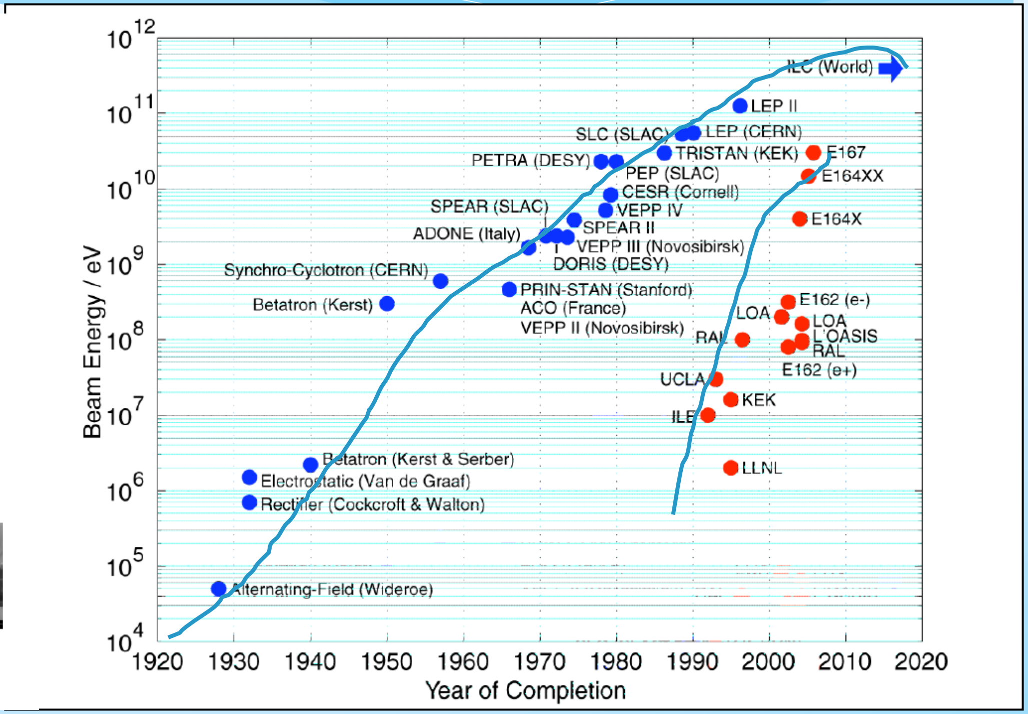


Goal: lower cost, more compact, higher gradient



laser-driven microstructures

- **lasers:** high rep rates, strong field gradients, commercial support
- **dielectrics**: higher breakdown threshold → higher gradients (1-5 GV/m), leverage industrial fabrication processes



The dream

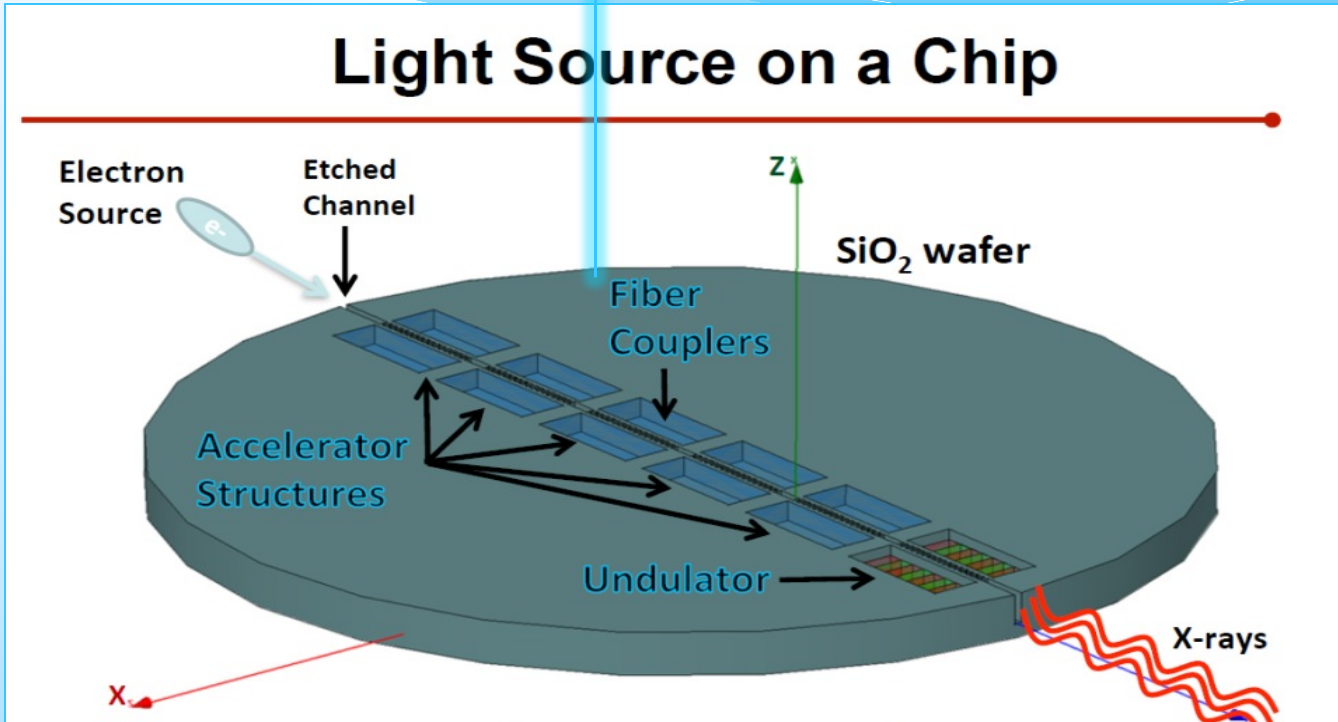
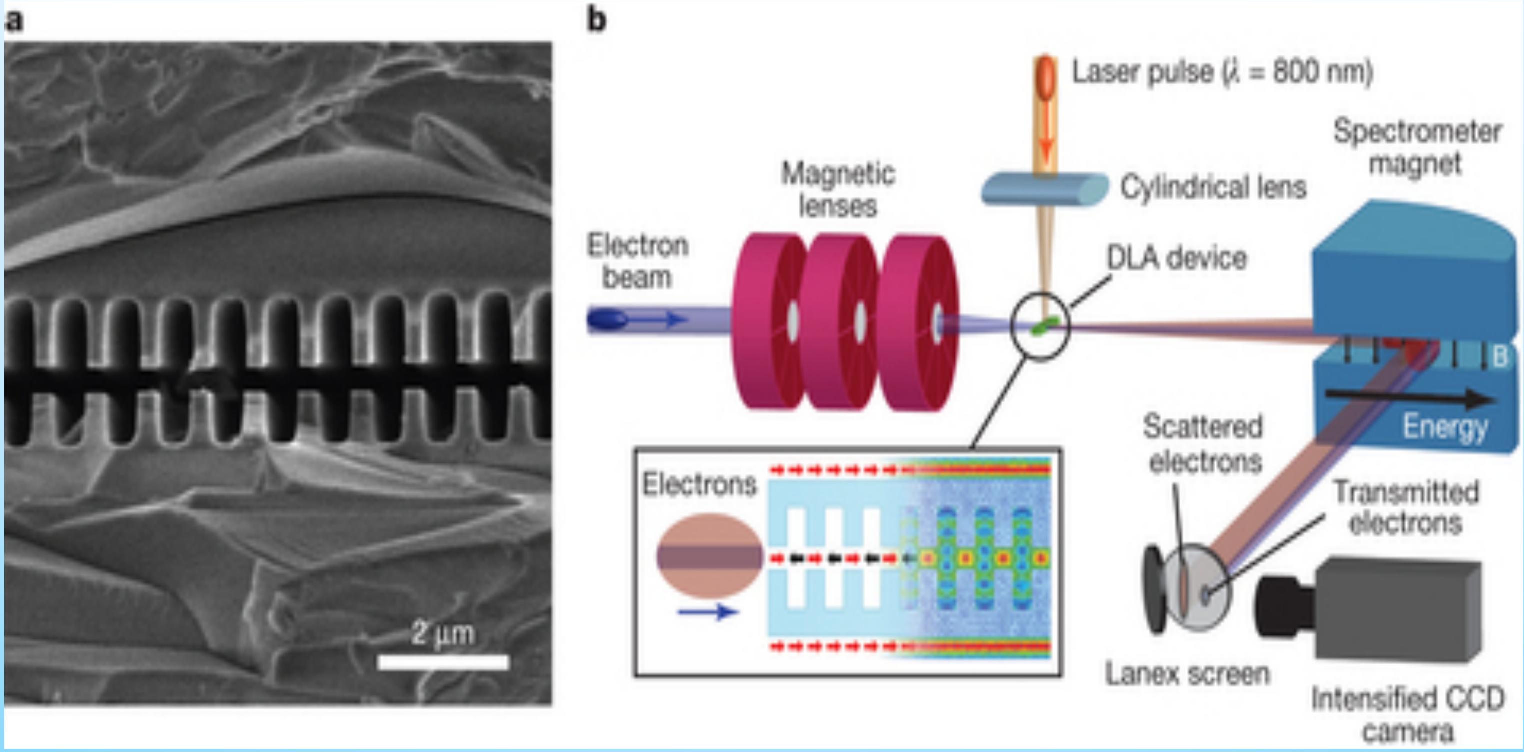


Image courtesy R. Byer

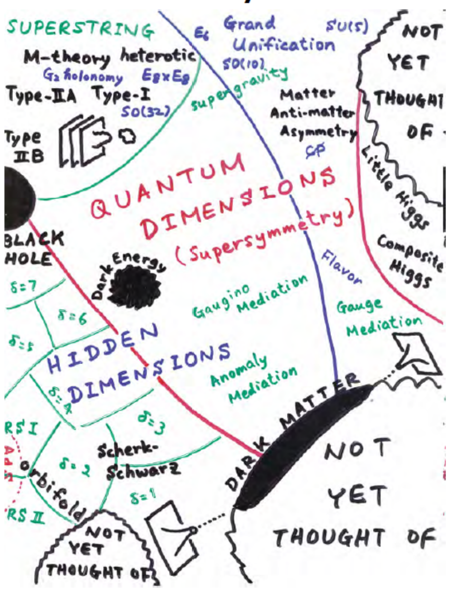
Dielectric acceleration

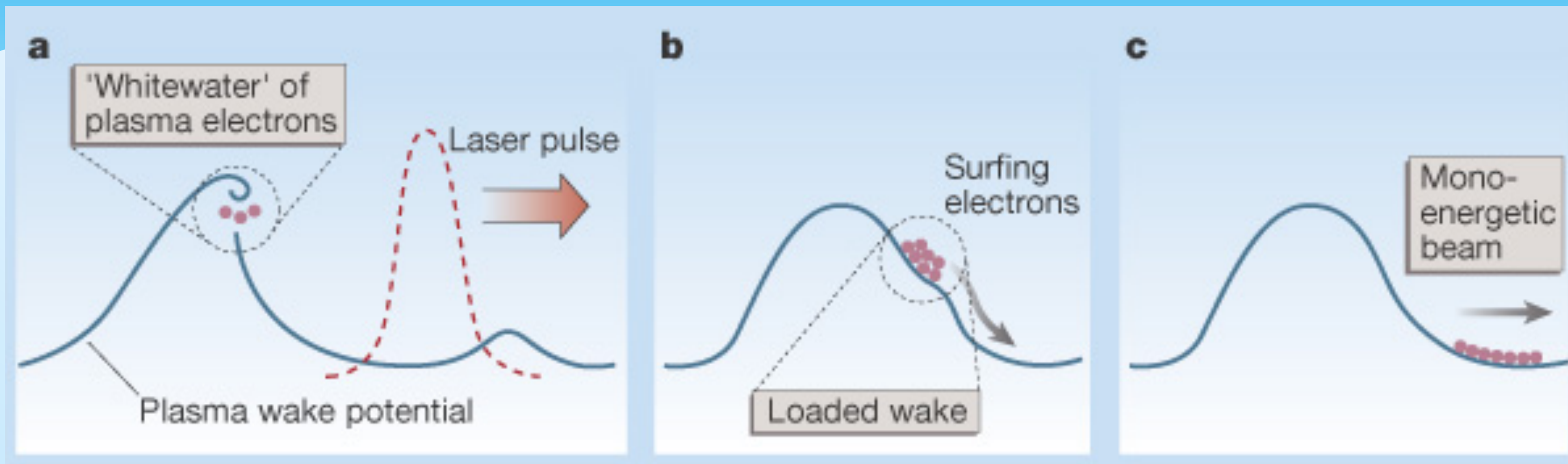


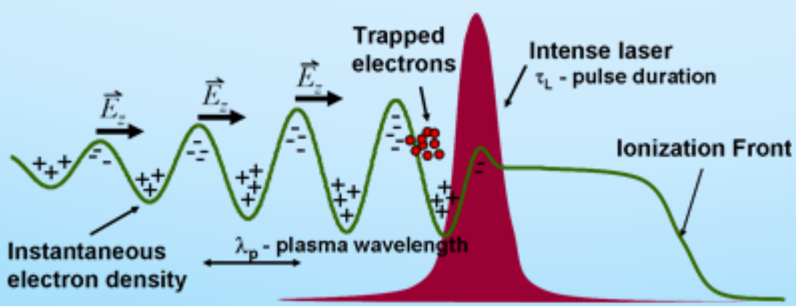
LIGHT AND PARTICLES in the 21-st century

Hitoshi Murayama's view of

Particle Physics in the 21st Century



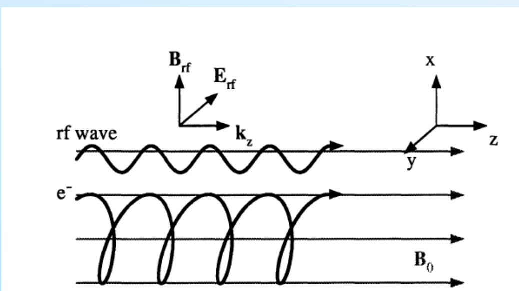

a
'Whitewater' of plasma electrons
Laser pulse
Plasma wake potential
b
Surfing electrons
Loaded wake
c
Mono-energetic beam

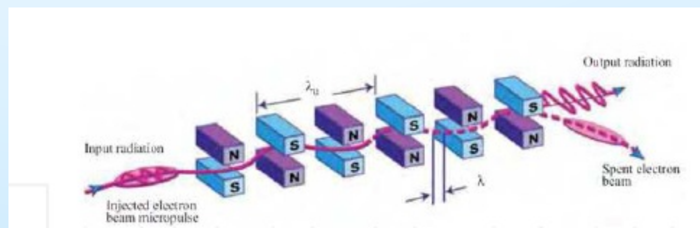

Trapped electrons
Intense laser
τ_L - pulse duration
Ionization Front
Instantaneous electron density
λ_p - plasma wavelength

ENEA *Frascati*

How many «free electron devices»?

- *For any kind of emission mechanism (Cerenkov, Smith Purcell…) a FEL device can be conceived*





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

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

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

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

$$\alpha \to K$$

$$\Omega = \frac{eB}{m_e}$$

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

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

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

$$\omega = \frac{\Omega_0}{\gamma} + k_z v_z$$

Interest For Plasma Fusion Applications

- Resonance condition

$$\gamma - \frac{n\Omega_P}{\omega} - N_{\|} u_{\|} = 0$$

electron cyclotron frequency in plasma

- *Parallel component* of the refractive index $\left(N = \frac{ck}{\omega}\right)$
- Resonance frequency 250 GHz
- Power 3 MW
- Efficiency >30%

Required Parameters

Main Project Parameters

- Operating Frequency – ***250 GHz***
- Pulse Duration:
- Phase I – up to ***10 us***
- Phase II – up to ***100 us***
- Phase III – from ***ms*** to ***CW*** operation
- Output Power – higher than ***500 kW***
- Efficiency:

Without Depressed Collector ~ ***20 %***

With Depressed Collector - above ***35 %***

An Exercise to fix Numbers Operating Frequency 250 GHz

* **Beam current 5 A**
* **Beam voltage** 700 kV
* **Longitudinal velocity spread** 0.3 – 0.5 %
* **Energy spread** 1 – 2 %
* **Cavity magnetic field** 5 T