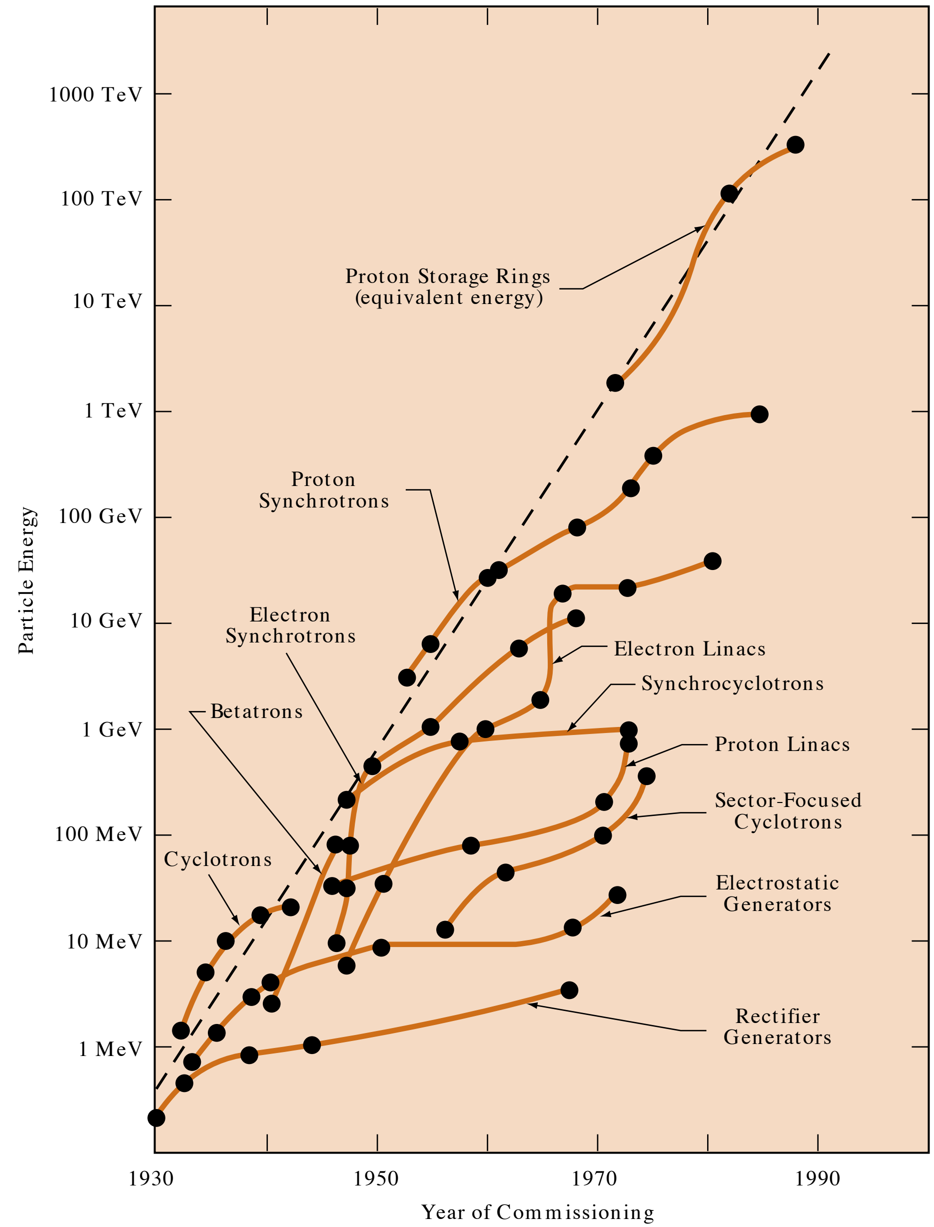
New Concept Acceleration and Accelerator Applications

Need for New Accelerator Concept

- Current Limiting Factor for achieving higher energy
  - Accelerator Gradient
    - <100 MeV/m ->Long Linac
  - Bending Field
    - ~10 Tesla -> Large Ring
- LHC 3.5 TeV
  - 27 Km circumference
- To reach 100 TeV
  - > 1000 Km Linac
  - ~250 Km Diameter Ring



Build a 100 TeV collider in Michigan?

Can Laser help?

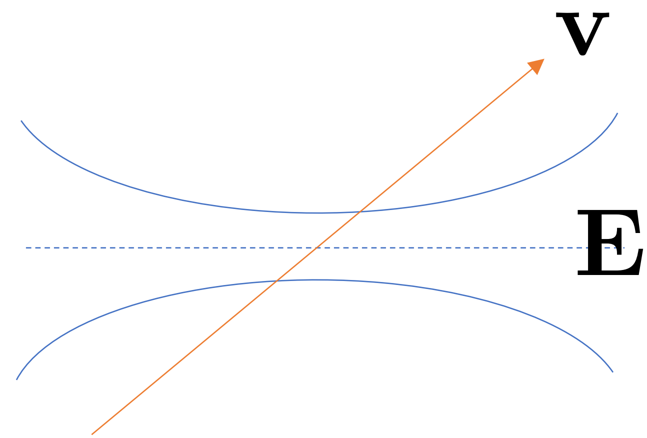
- Modern Laser can provide large peak power and is focused to small cross section.
  - Example: 100TW peak power, 800nm laser is focused to a round spot of 10 micron

$$|S| = \frac{E^2}{Z_0}$$

  - This generates ~10000 GV/m electric field!
- Question is:
  - Can we really use such large field

Lawson-Woodward theorem

Energy exchange:



$$W = q \int_{-\infty}^{\infty} \boldsymbol{v} \cdot \boldsymbol{E}(\boldsymbol{r}_0 + \boldsymbol{v}t, t) dt$$

$$\boldsymbol{E}(\boldsymbol{r}, t) = \int d^3k \tilde{\boldsymbol{E}}(\boldsymbol{k}) e^{i\boldsymbol{k}\cdot\boldsymbol{r} - i\omega t}$$

$$W = q\boldsymbol{v} \cdot \int_{-\infty}^{\infty} dt \int d^3k \tilde{\boldsymbol{E}}(\boldsymbol{k}) e^{i\boldsymbol{k}\cdot(\boldsymbol{r}_0 + \boldsymbol{v}t) - i\omega t}$$

$$= 2\pi \int d^3k \, q\boldsymbol{v} \cdot \tilde{\boldsymbol{E}}(\boldsymbol{k}) e^{i\boldsymbol{k}\cdot\boldsymbol{r}_0} \delta(\omega - \boldsymbol{k} \cdot \boldsymbol{v})$$

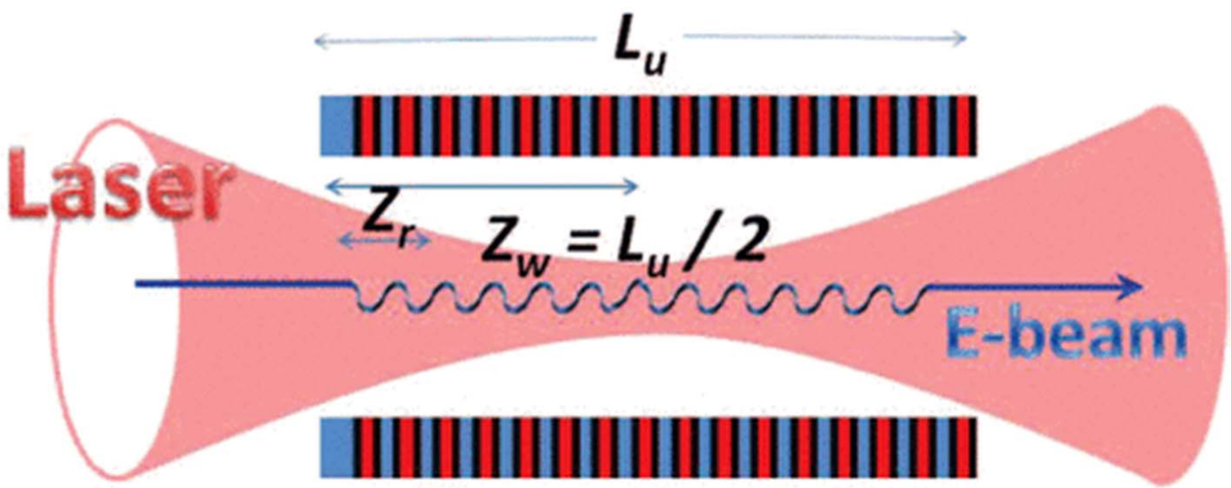
Vanish!!

No energy exchange is allowed with assumption:

- Laser in Vacuum
- Particle 's velocity do not change.

Walk-around: IFEL

- It is a reverse process of FEL, the beam pass through undulator, and gain energy from external EM wave.



Energy gain of IFEL

Planar Wave:

$$E_x(z,t) = E_0 \cos(\omega t - kz)$$

Velocity modulation

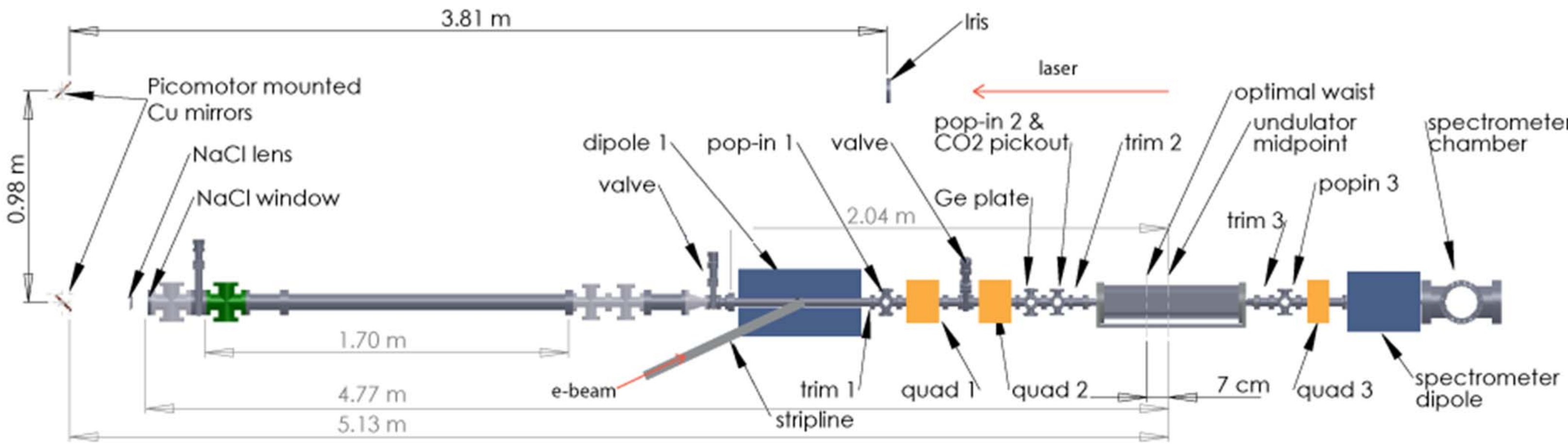
$$v_x = \frac{cK}{\gamma} \sin(k_u z)$$

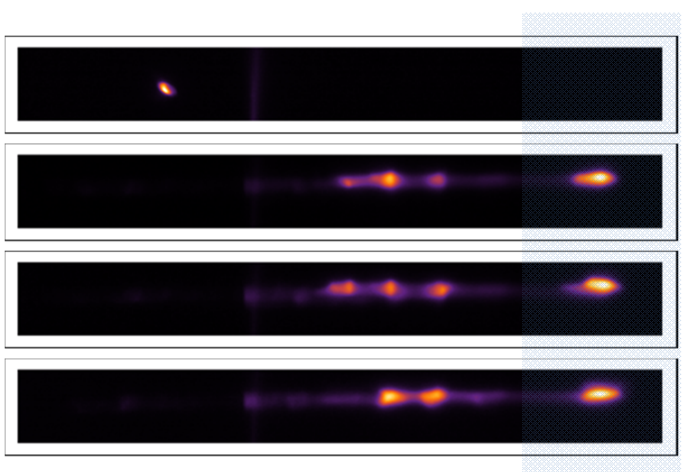
Energy Gain

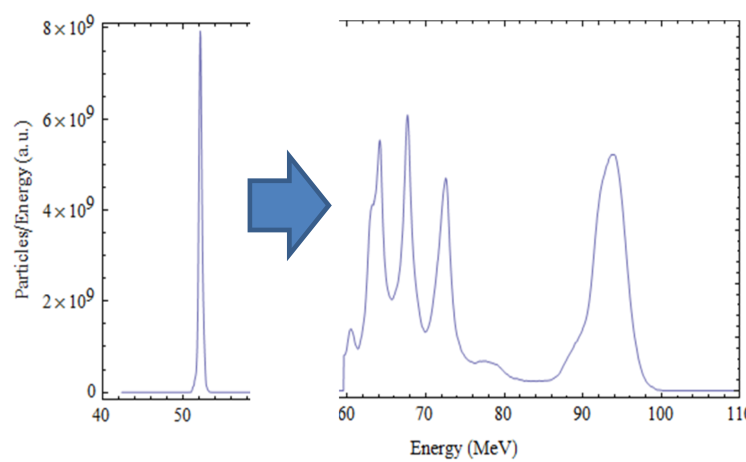
$$\Delta E = q \int E_x v_x dt$$

$$= \frac{qcK}{\gamma} \int sin(k_u z) \cos(\omega t - kz)|_{z=z_0+\bar{v}_z t} dt$$

IFEL Experiment







Demonstrated IFEL Acceleration

- Experiment demonstrates:
  - > 50 MeV energy gain
  - ~100 MeV/m Gradient

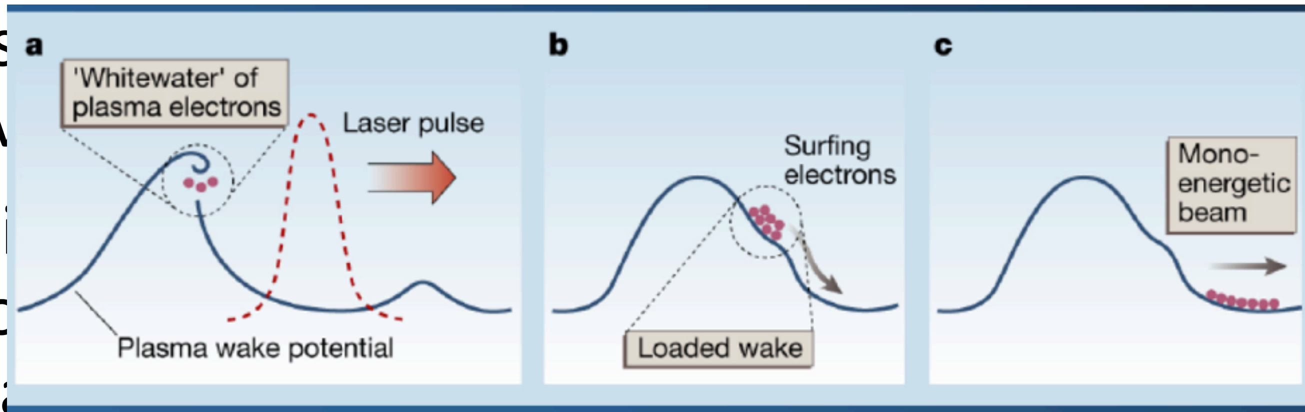
$$W = \frac{qKE_0L_u}{2\gamma}\sin\left((k+k_u)z_0\right)$$

- Features of IFEL
  - Well controllable, via undulator
  - Decent gradient, degrade with higher energy !
  - Good Beam quality (Energy spread)

- Still far from the gradient we are dreaming!

Plasma Acceleration

- Firs … s.
  Rev …
- ’Exi … m^2
  sho … eld
  giga … neter
  of acceleration distance.’



Dimensionless vector potential of laser :

$$a_0 = \frac{eE_0\lambda_0}{2\pi mc^2} = \frac{eE_0}{mc\omega_0} = \frac{eA_0}{mc^2}$$

Plasma Frequency

$$\omega_{\rm pe} = \sqrt{\frac{n_{\rm e}e^2}{m^*\varepsilon_0}}$$

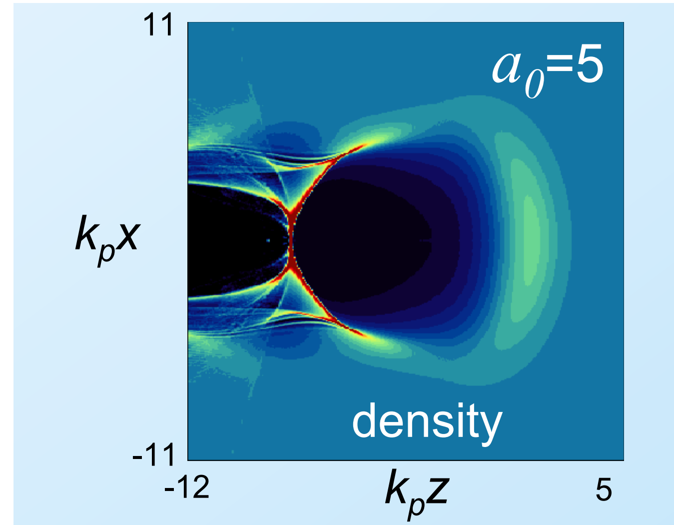
Plasma Wave Excitation

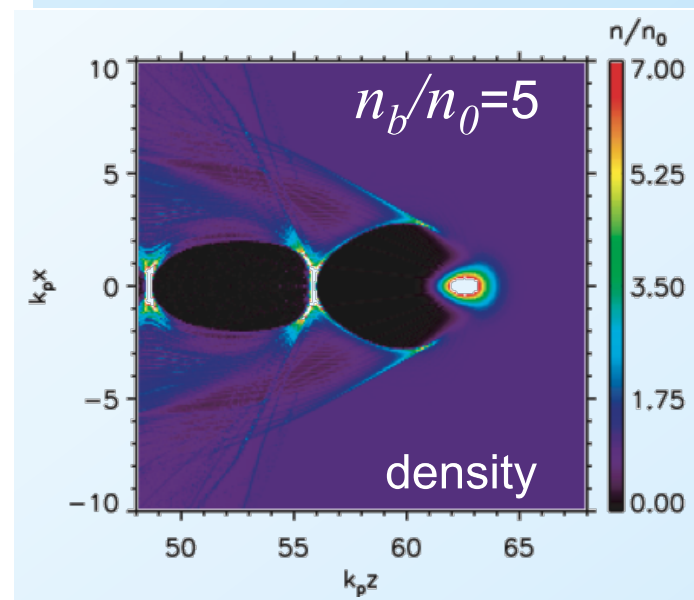
- Driver
  - Laser Driver

    Ponderomotive force
  - Beam Driver

    Space – charge fields
- Regime of option
  - Linear Regimes, non-relativistic electron motion
  - Nonlinear Regimes, relativistic electron.

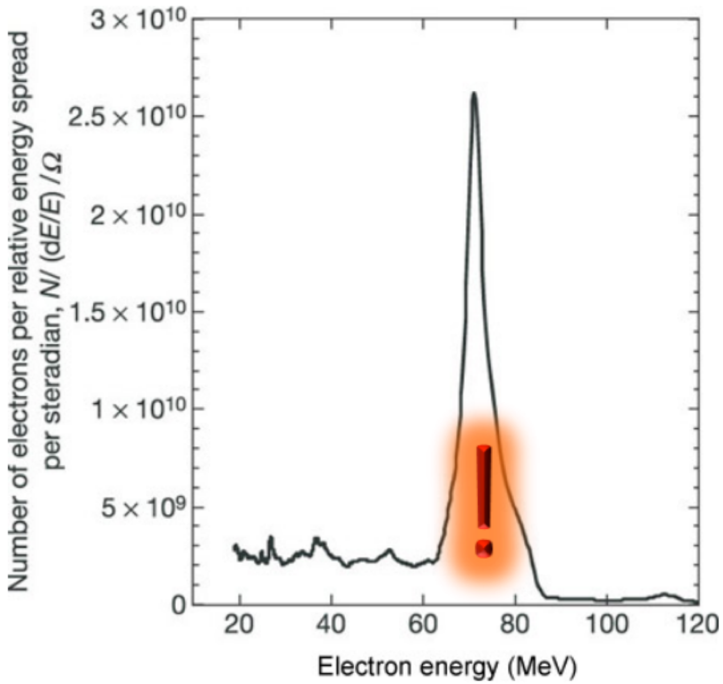
$$E \sim \left(\frac{mc\omega_p}{e}\right) \approx (96\mathrm{V/m})\sqrt{n_0[\mathrm{cm}^{-3}]}$$

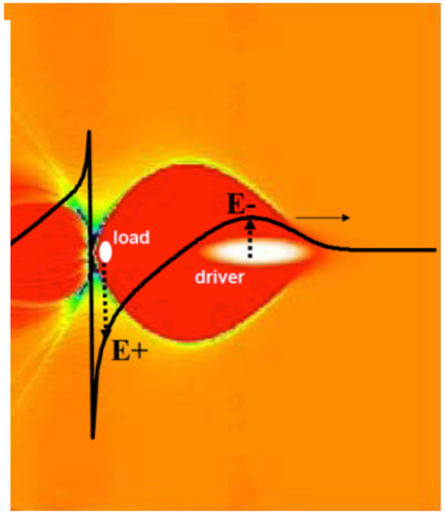




Nonlinear Regime

Dream beam is created using nonlinear regime, 2004.

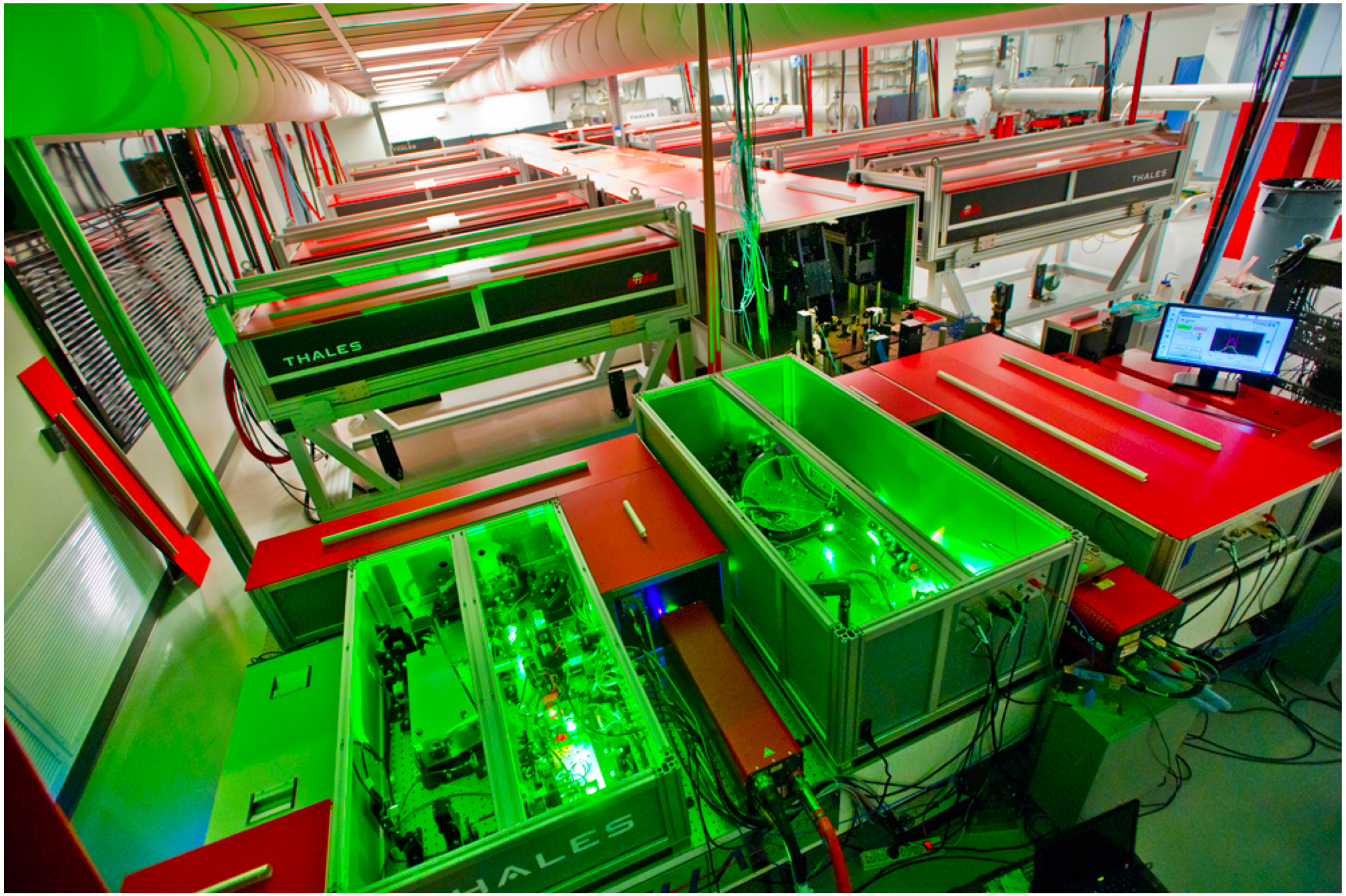




Few percent energy spread is achieved!

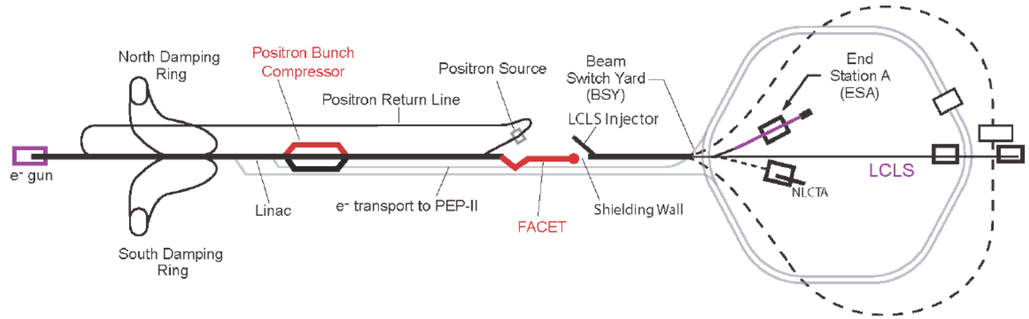
Laser system

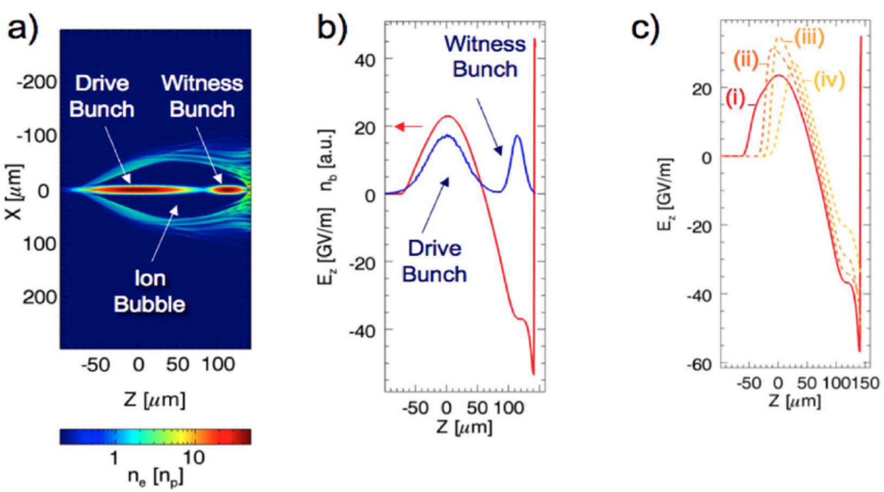
~ Peta watt laser is common in latest laser-plasma accelerator. Bella laser below.

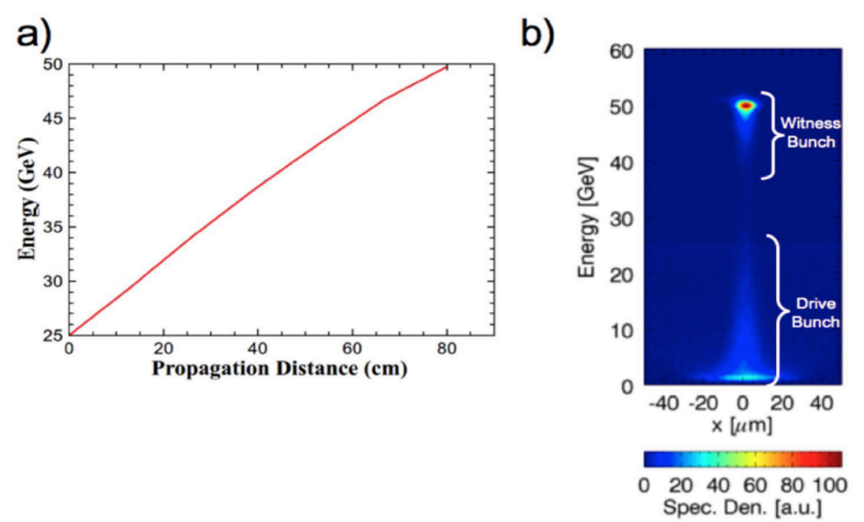


Beam Driven PWA

Parameter	Uncompressed	Compressed	Two-bunch[1]
Particle[2]	Electrons	Electrons	Electrons
Energy	20 GeV	20 GeV	20 GeV
Charge/pulse[3]	1.6 nC	1.6-3.2 nC	
IP Spot Size[4]	30 μm x 30 μm	30 μm x 30 μm	
Bunch Length[5]	500 μm	30 μm	
Rep. Rate	1-30 Hz	1-30 Hz	1 Hz







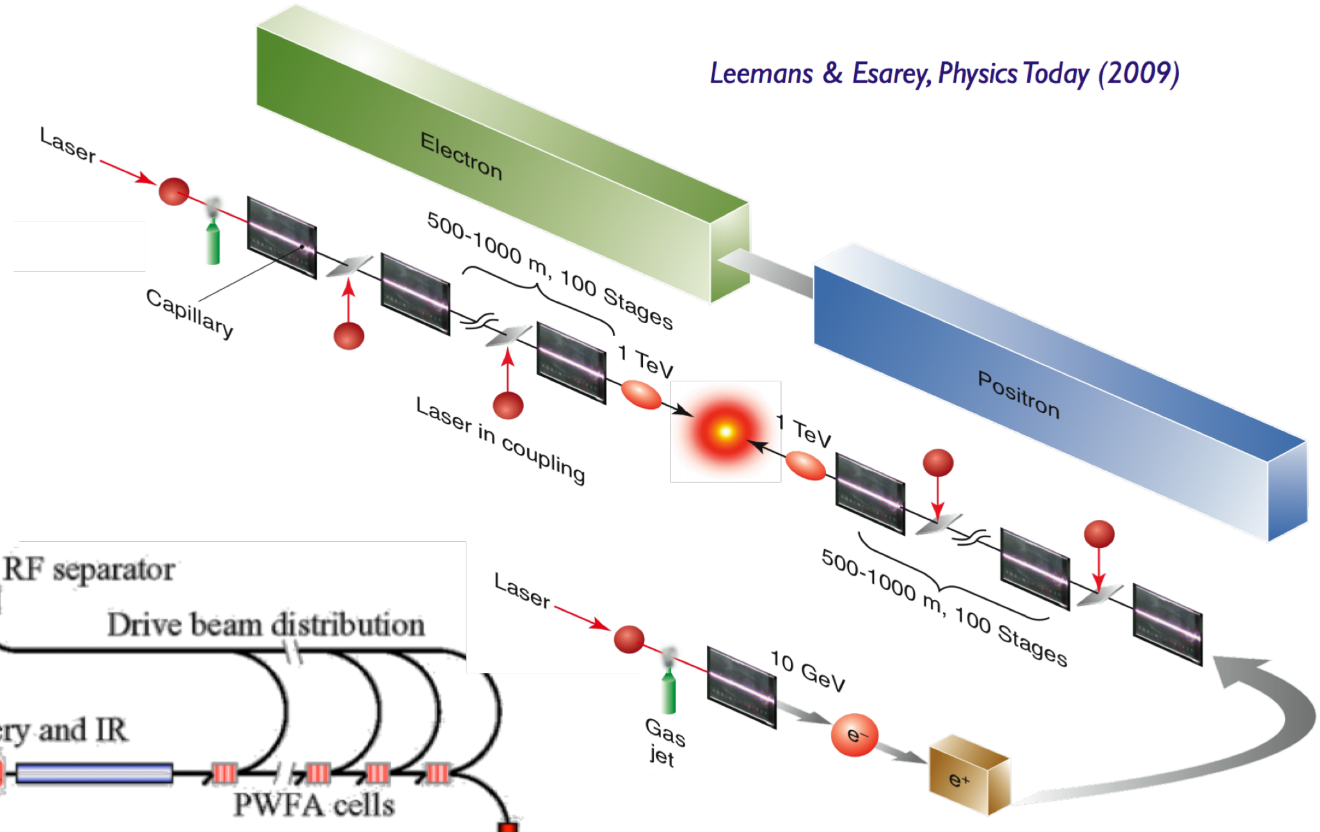
Transformer ratio of 2
Good beam loading efficiency

Drive Bunch
30 micron
3e10

Witness Bunch
10 microns
1e10

Larger Scale PWA

Leemans & Esarey, Physics Today (2009)



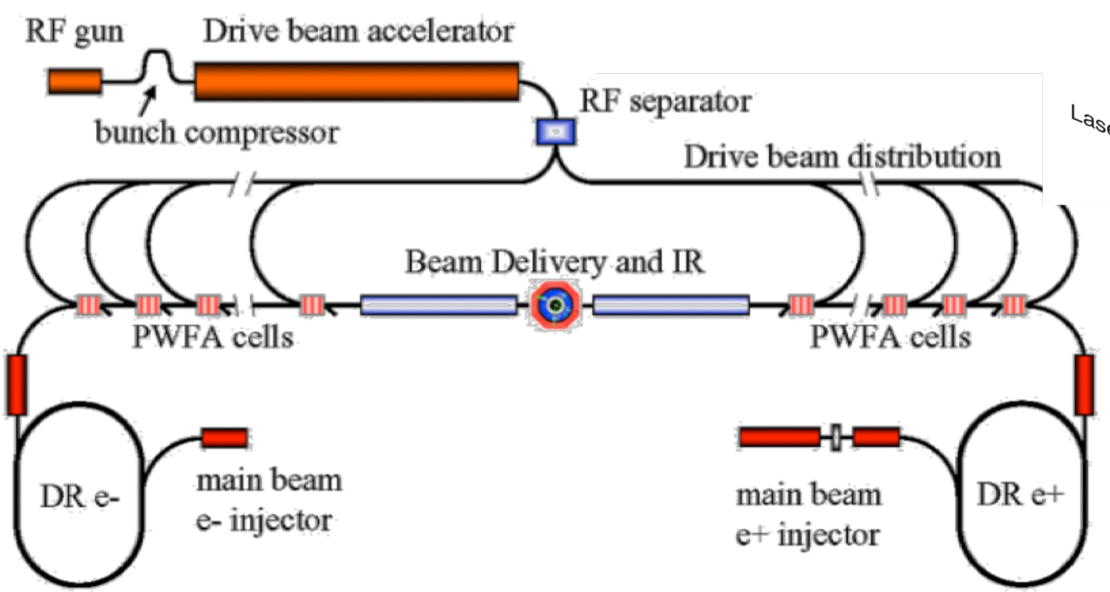
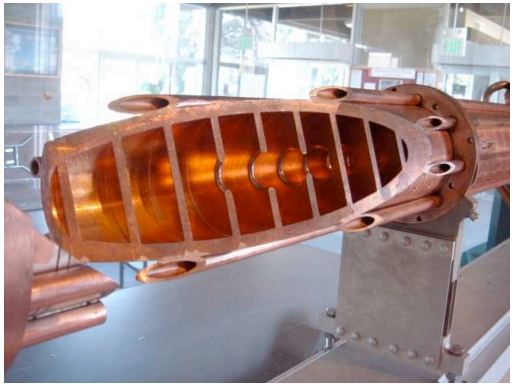
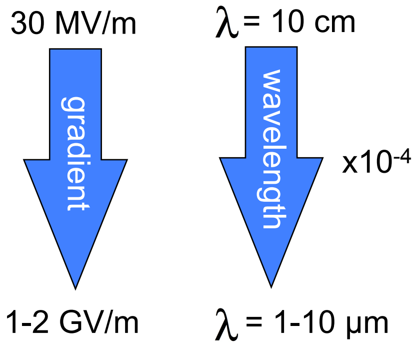


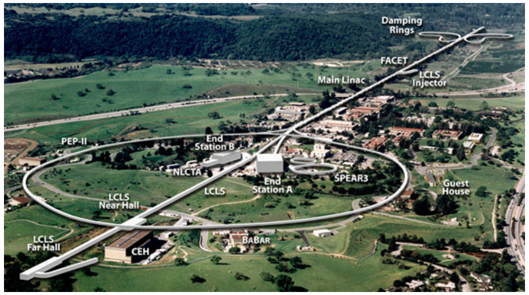
Figure 1: Concept for a multi-stage PWFA-based Linear Collider.

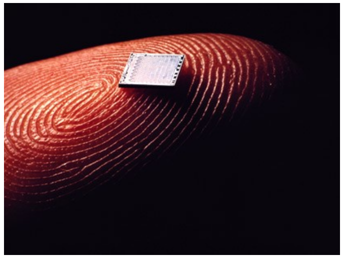
Dielectric Laser Acceleration

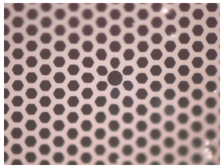
- General Idea:
  - Scale down the Acc. Structure
- Laser + Dielectrics
  - High rep rate, High field
  - High breakdown field
  - Mature fabrication process

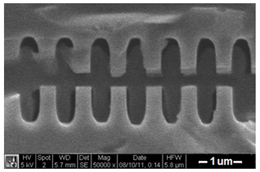


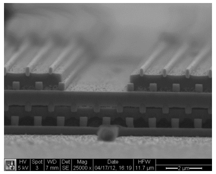






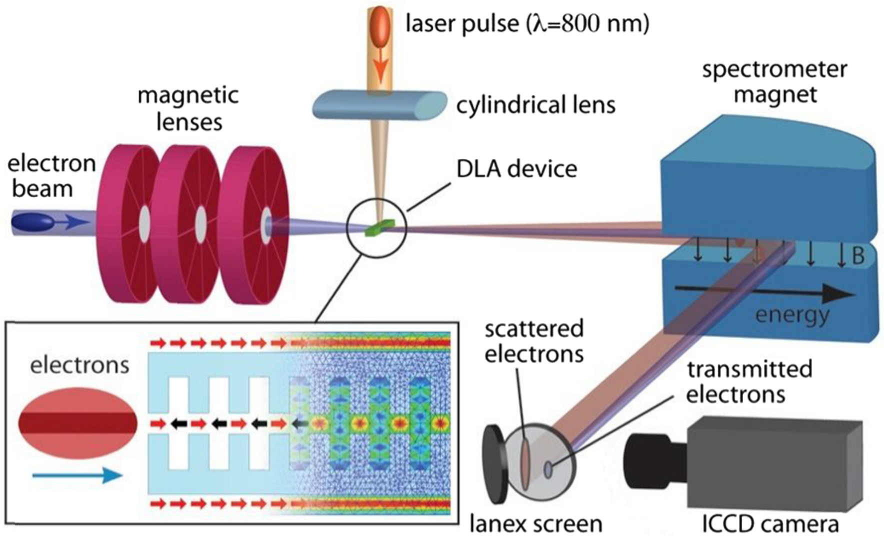


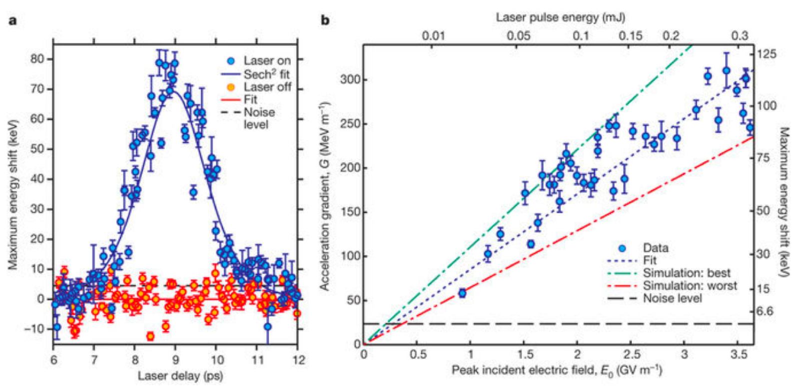


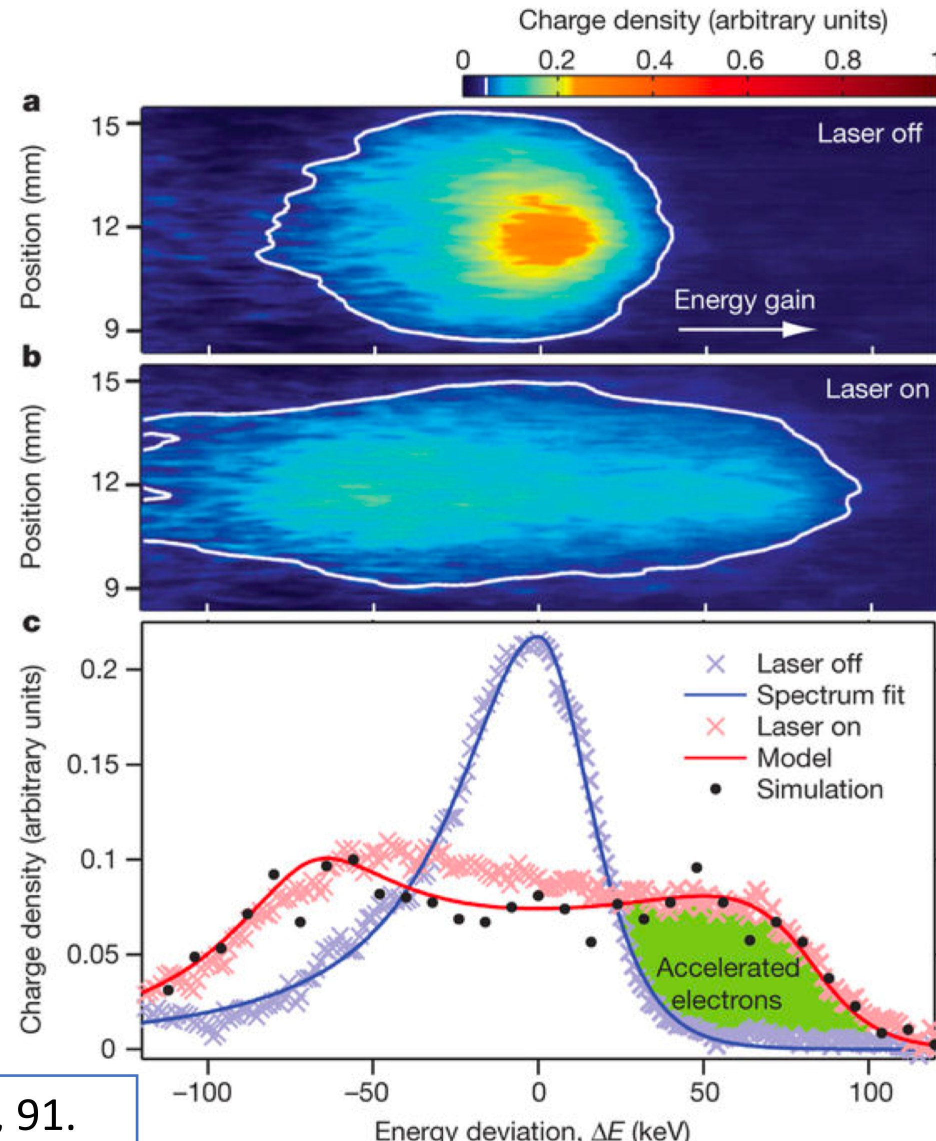


@ R. J. England

Experiment Verification







Peralta, E. A., et al., 2013, Nature (London) 503, 91.

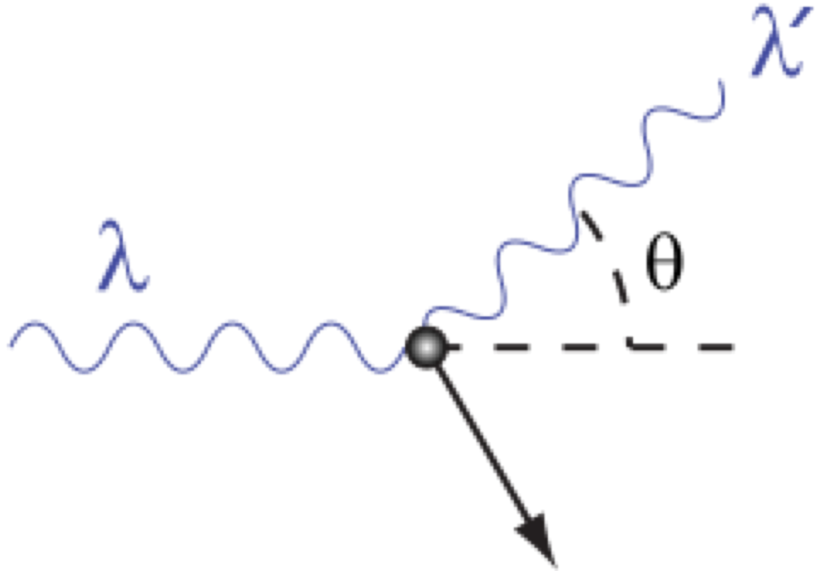
New Applications

Compton Scattering

- Compton scattering can be used to build compact X-ray source
- We start with the rest frame of electron:

Compton wavelength

$$\lambda' = \lambda + \frac{h}{m_e c}(1 - \cos\theta)$$



Quantum correction of the Thomson scattering.

Doppler effect

- Transform from the rest frame to the lab frame.

$$f_o = \frac{f_s}{\gamma(1+\beta\cos\theta)}$$

- With the ‘back scattering’, i.e. the scattered angle is ~Pi, the wavelength relation in lab frame reads:

$$\lambda' = \frac{\lambda}{4\gamma^2}(1+\gamma^2\theta^2)$$

- The energy ratio:

$$E_i : E_i' : E_o = 1 : 2\gamma : 4\gamma^2$$

Cross Section

- The cross section of the Thomson scattering is:

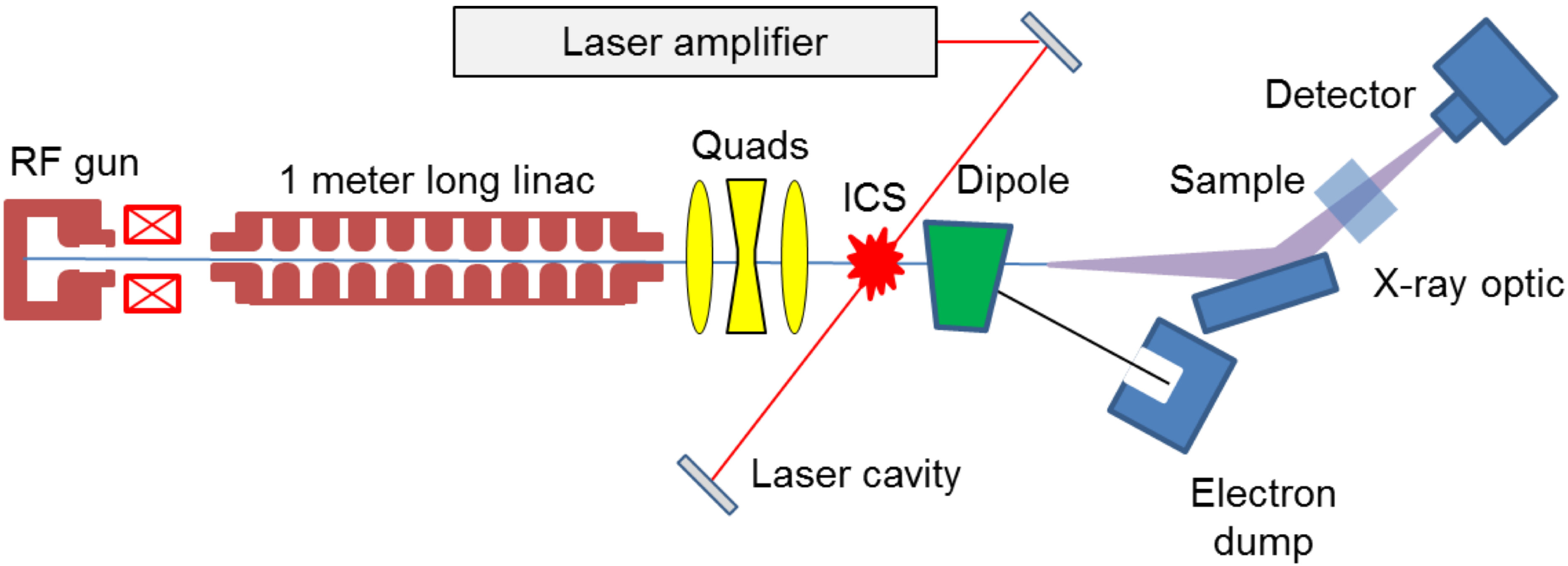
$$3\pi r_0^2/8$$

- The Klein-Nishina formula gives

$$\frac{d\sigma}{d\Omega} = \alpha^2 r_c^2 P(E_\gamma, \theta)^2 [P(E_\gamma, \theta) + P(E_\gamma, \theta)^{-1} - 1 + \cos^2(\theta)]/2$$

Where P is the ratio of the photon energy before and after collision. When the electron energy is much larger, the formula reduces to Thomson case.

Example, a compact x-ray source



Proposed by W. Graves

Medical Application

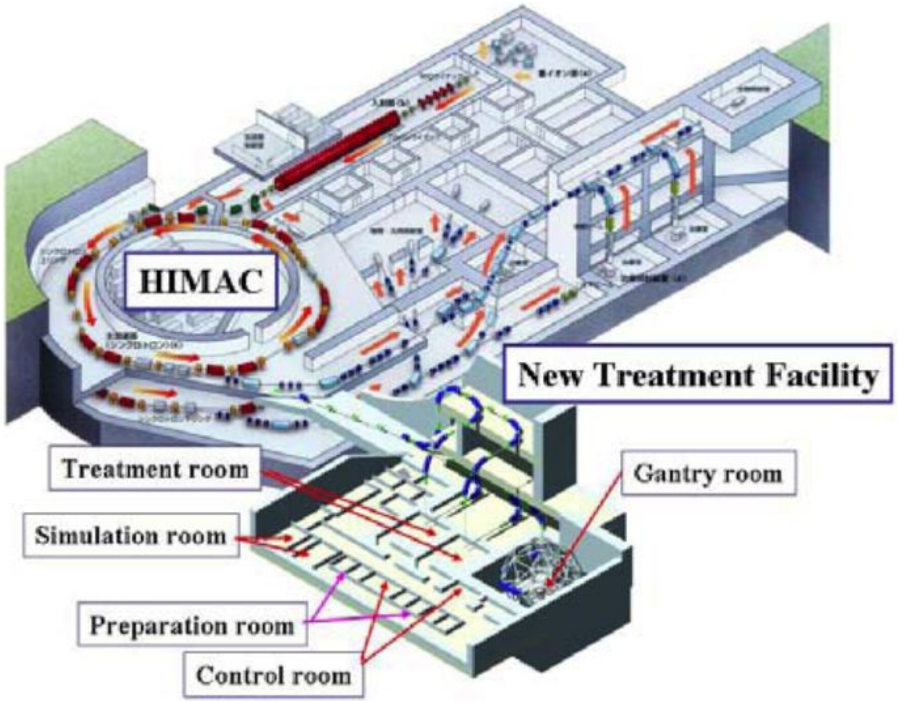
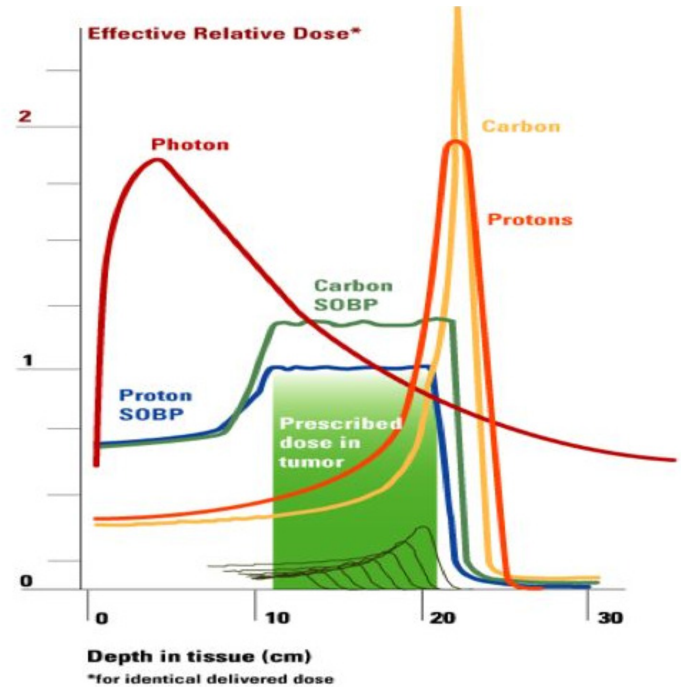


Figure 3: Schematic view of HIMAC. The lower part depicts the new treatment facility addition (2011). (K. Noda, NIRS)



Medical Application around World

Table 3: Physical Characteristics of Ion Beam Facilities, Existing and Under Construction

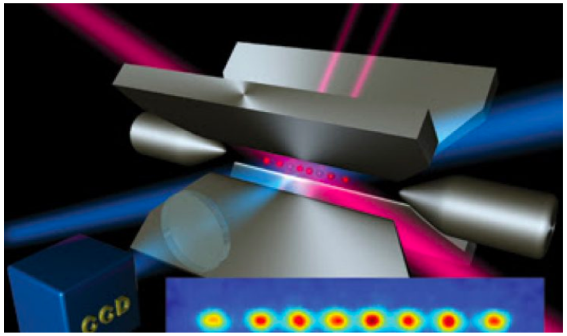
	HIMAC Chiba	**HIBMC Hyogo**	**HIT Heidelberg**	**CNAO Pavia**	**GUNMA Maebashi**	**Marburg**
Particles	p, C, O, Ar, Xe	p, He, C	p, He, C, O	p, He, C, O	C	p, C
Accelerator	2 Synchrotrons	Synchrotron	Synchrotron	Synchrotron	Synchrotron	Synchrotron
Ion Sources	PIG for low Z; ECR for high Z	2 ECR sources	2 ECR sources	2 ECR sources	ECR source	2 ECR sources
Injector	RFQ (8 to 800 keV/u) and Alvarez LINAC (0.8 to 6 MeV/μ) at 100 MHz	RFQ (1MeV/μ) and Alvarez LINAC (5 MeV/μ)	7 MeV/u linac injector	RFQ (8 to 400 keV/μ) and IH-DTL LINAC (to 7 MeV/μ)	RFQ and APFIH	
Particle Energy (MeV/μ)	C (420) Ar (800)	p & He(70- 230) C (70 - 320)	50 - 430	p: 250 C: 60 - 400	C only: 400	100-430
Beam Intensity, particles per spill (pps)		p: 7.3×10^{10} He: 1.8×10^{10} C: 1.2×10^{9}	p: 4×10^{10} He: 1×10^{10} C: 1×10^{9} O: 5×10^{8}	p: 2×10^{10} C: 4×10^{8}	C: 1.2×10^{9}	C: 3×10^{8}
Repetition Rate		p: 1 Hz He C: 0.5 Hz				
Spill Length (msec)		400		250 - 10,000		
Treatment Rooms	1 H, 1 V, and 1 H&V 1 gantry (planned)	p: 1 H and 2 gantry rooms C: 1 H&V and 1 45 degree	2 H and 1 gantry room	2 H and 1 H&V	H, V, H&V; no gantry	3 H and 1 45 degree
Beam Delivery Technique	Passive scattering		Intensity controlled 3D raster scan	Intensity controlled 3D raster scan	Passive, respiration gated	
Field Size (cm^2)		15 x 15	20 x 20	20 x 20	15 x 15	
# Pts Treated or Planned /Year	5189 (2010.2)	515 (2009.3)	> 1,000			1500-2000
First patient	1994	2001	2009	2010	2010	2010

Quantum Computing ?!

We need individual control qubits which can be in two base states: $|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$

and its linear combination and entangled states.

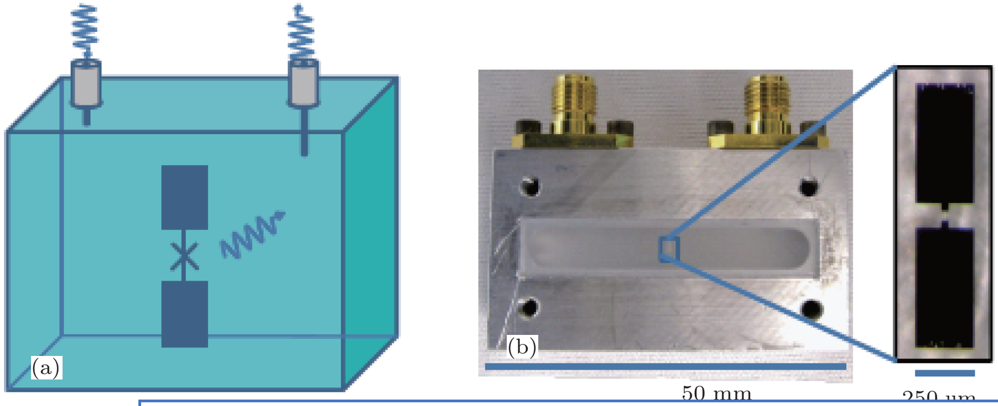
$$\alpha|0\rangle + \beta|1\rangle$$



Ion trap

It is important to ensure the decoherence time of the Quantum state, while keep the strong coupling to the states to realized the 'logic gate'.

The decoherence time is largely improved in cQED from ns level to ms level in recent years, taking advantage of the high quality factor of the superconducting cavity, working at 10-20 mK.



Cavity Quantum ElectroDynamics (cQED)
2012 Nobel Prize