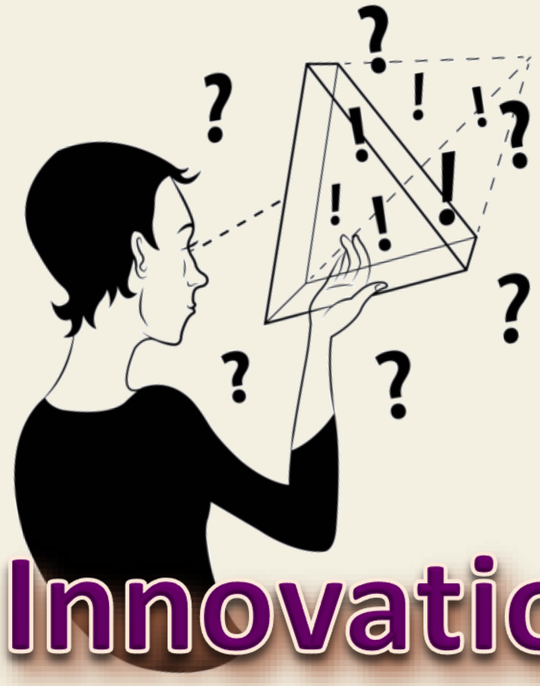
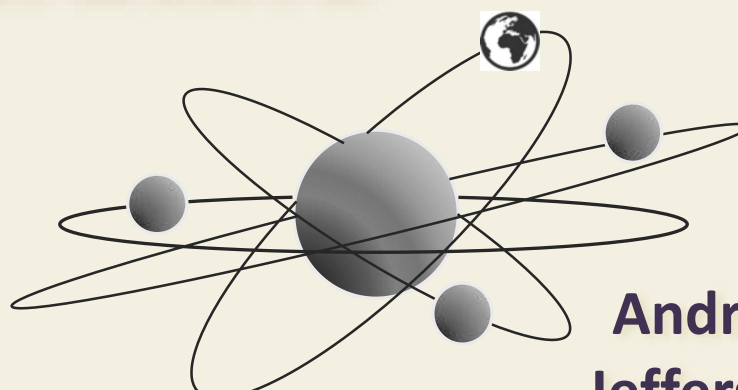


Innovation Techniques in Accelerators

LHC sketches by Sergio Cittolin (CERN)



Andrei Seryi

Jefferson Lab

International Accelerator School, Canada, Saskatoon

Lecture 02, 18 July 2023

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    - **VITA – Virginia Innovative Traineeship in Accelerators**
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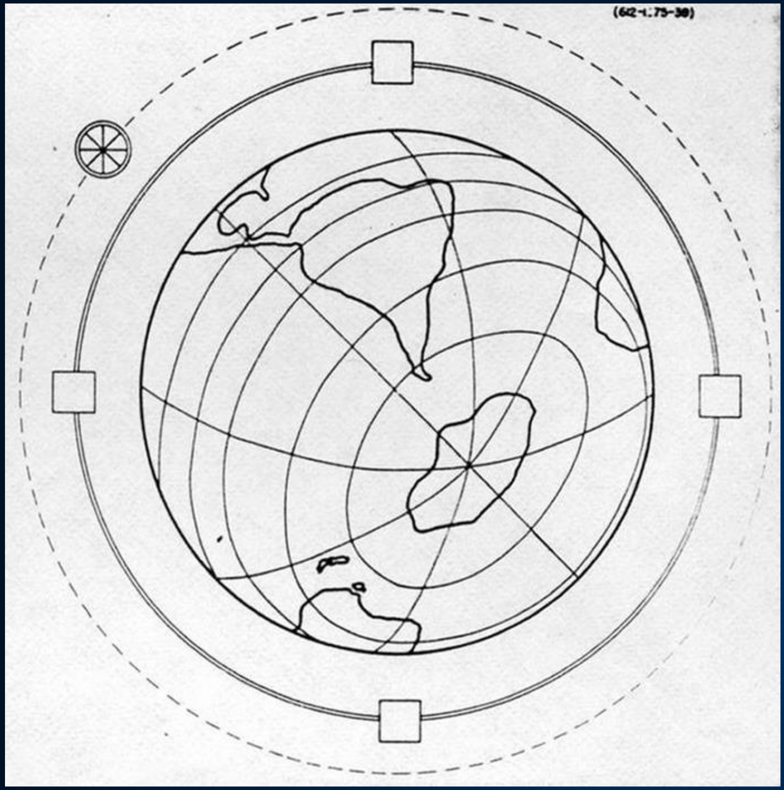
- **My co-author for the 1st and updated 2nd edition of the book "Unifying Physics of Accelerators, Lasers and Plasma" Elena Seraia**
  - **https://www.unifyingphysics.com/**
- **CERN for "eBook for all!" program that enabled conversion of the 1st edition of "Unifying Physics…" to Open Access**

Lecture materials

- **Slides are available at**
  - https://www.unifyingphysics.com/

  - **See section Resources**
  - **You can also access the 1st edition of the book which is now Open Access**

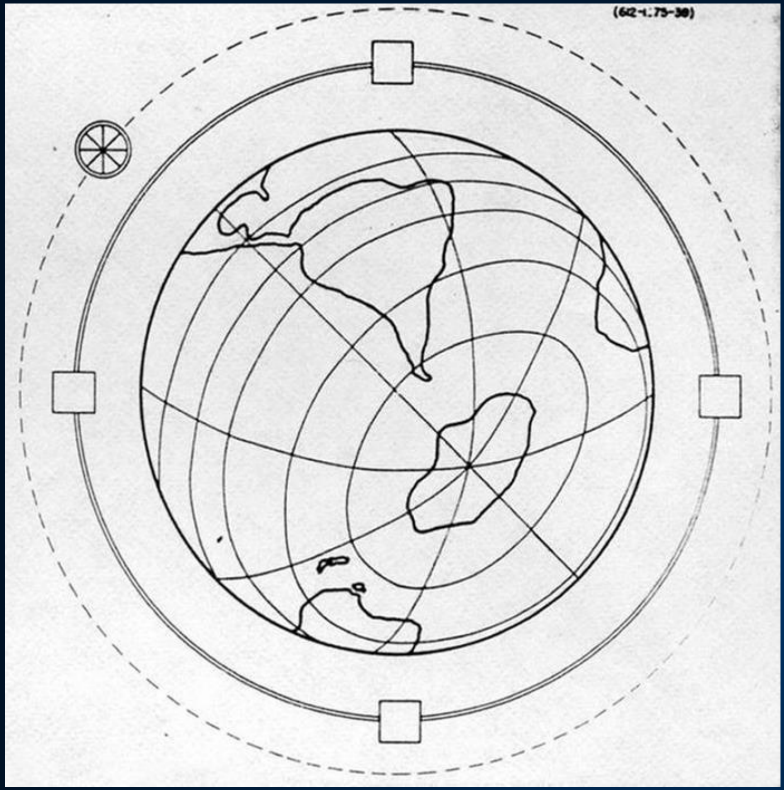
Evolution of accelerators



In 1954 Enrico Fermi presented, in his lecture, a vision of an accelerator that would encircle the Earth, and would attain highest possible energies

Would this be indeed a natural evolution of accelerators?

Evolution of accelerators



Enrico Fermi Earth accelerator, 1954

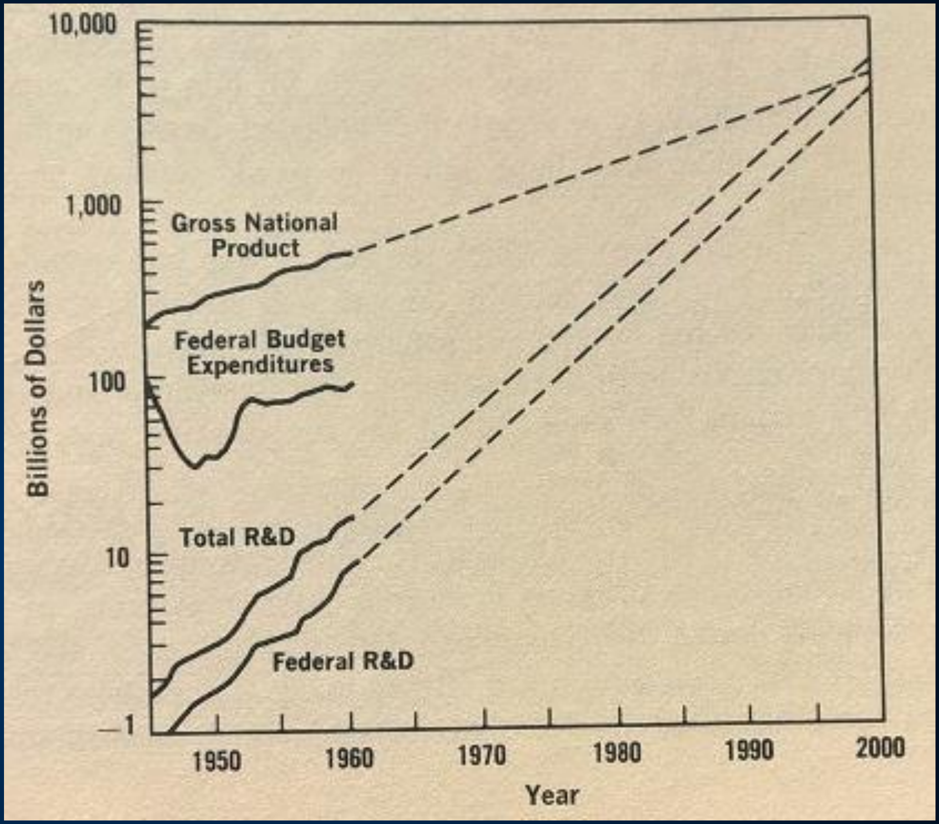
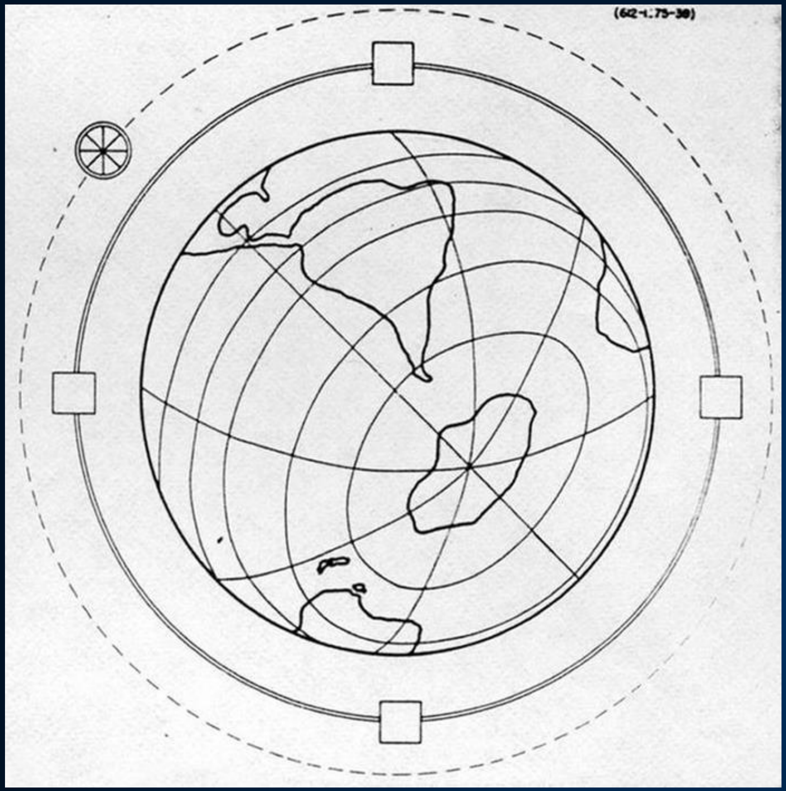


Fig 6, GNP and R&D: Failure of naïve extrapolation.
"The Year 2000", 1968, K. Herman, A. Wiener

Would this be indeed a natural evolution of accelerators?

No. And not only because R&D budget is now not growing faster than GDP

Evolution of accelerators



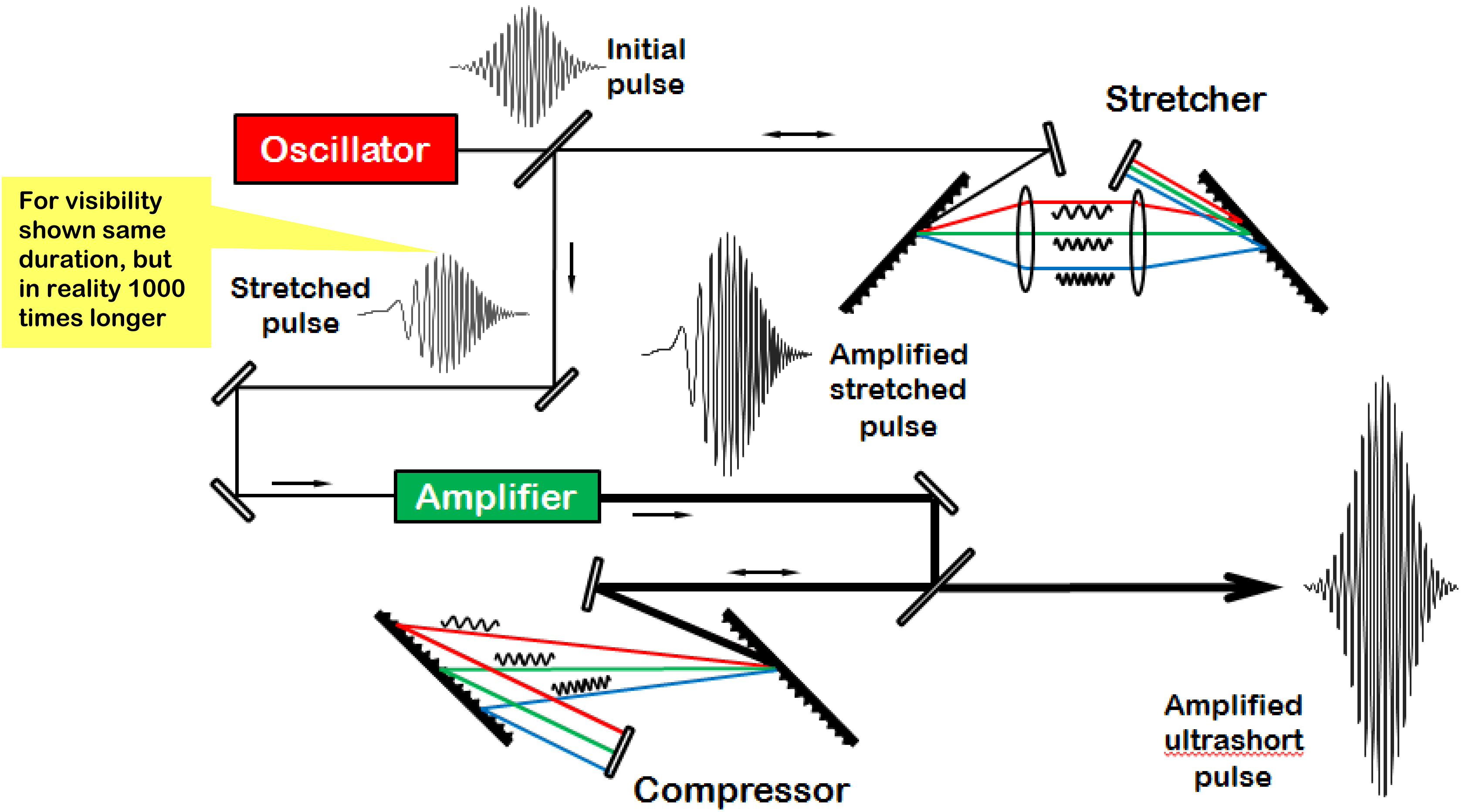
Enrico Fermi Earth accelerator, 1954

Would this be indeed a natural evolution of accelerators?

No.

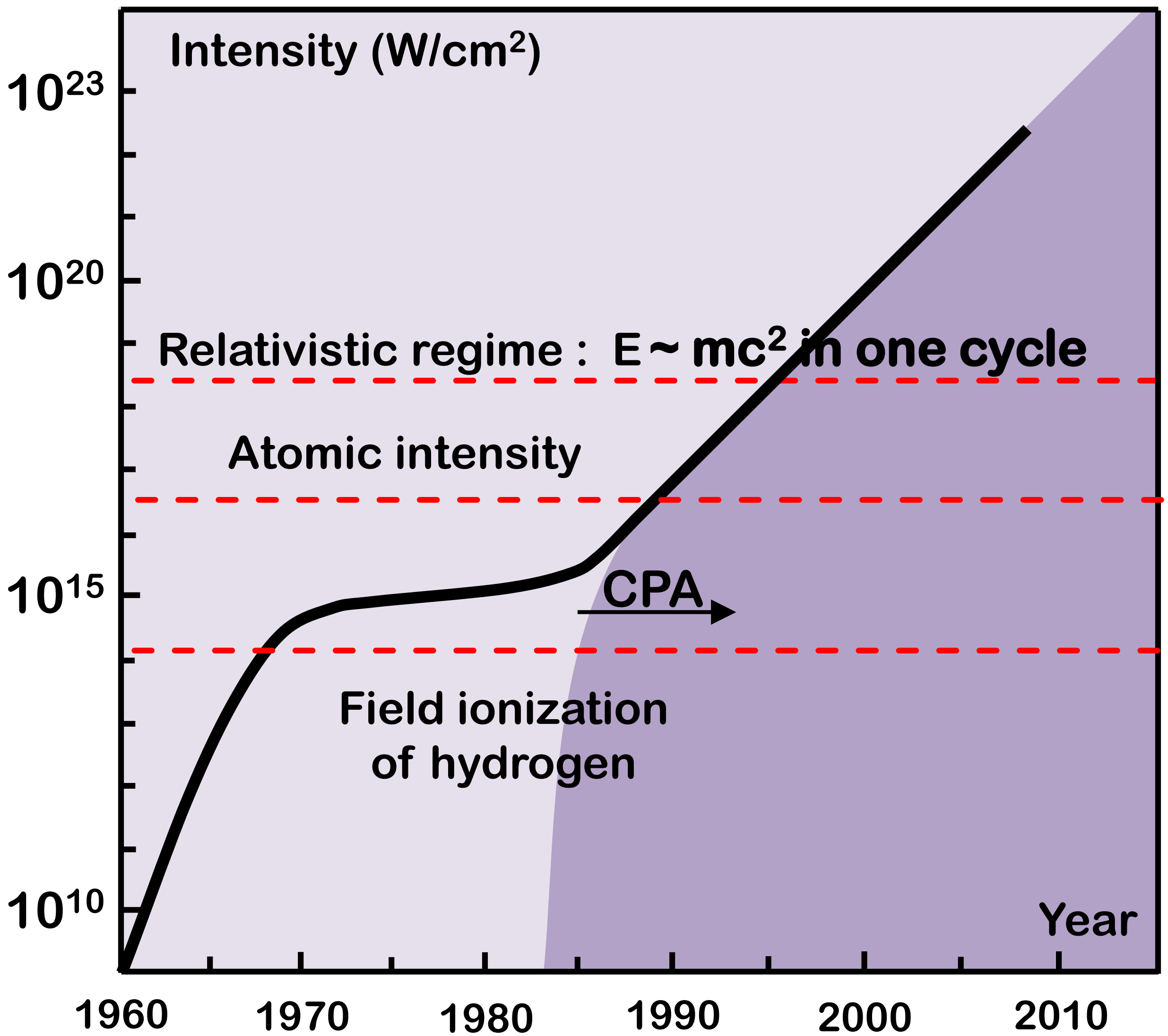
Increasing the size or base of the experiment, to increase precision, with proportional or event faster increase of the cost, would unlikely be accepted by governments and society

CPA – Chirped Pulse Amplification



- **CPA: pulse stretching and compressing using time-energy correlation**

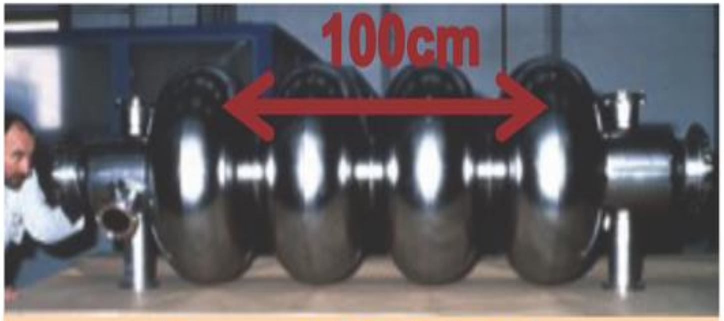
CPA invention: exponential growth of laser power



Progress in peak intensity since laser invention in 1960

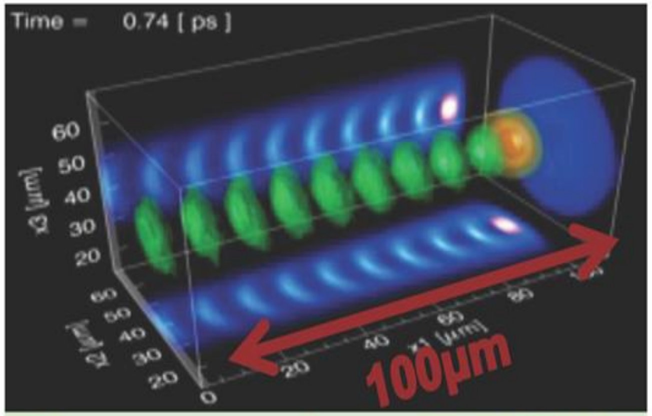
27. Cheap short-living objects

- Replace an expensive object with a multiple of inexpensive objects, comprising certain qualities (such as service life, for instance).



$$E_z < 100\,\mathrm{MV/m}$$

Accelerating structure, metal (normal conductive or super-conductive)



$$E_z = m_e c\omega_p / e \approx 100\,\mathrm{GV/m}$$

"Accelerating structure" produced on-the-fly in plasma by laser pulse

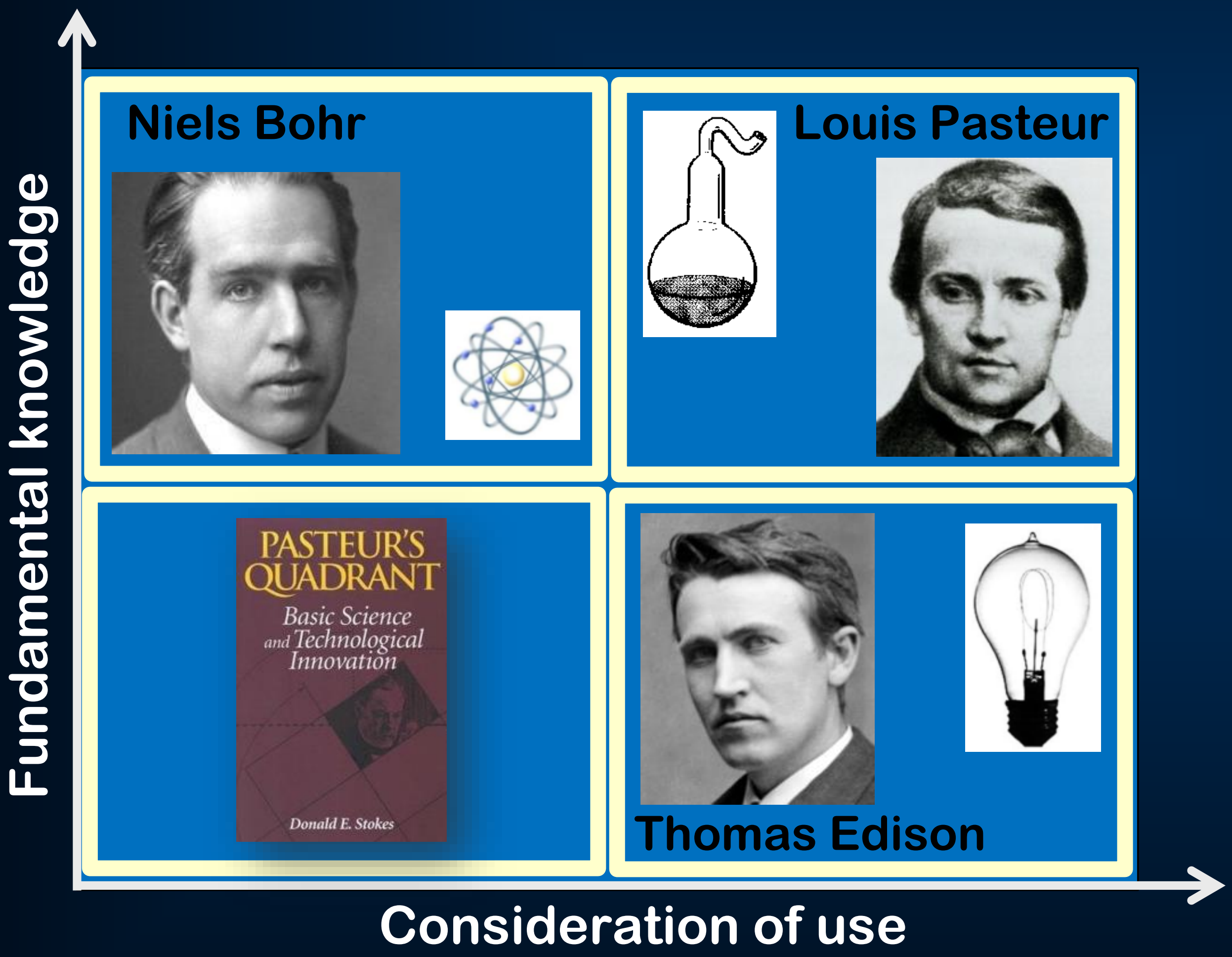
Plasma acceleration

Let’s now talk about evolution of synchrotron light sources and FELs

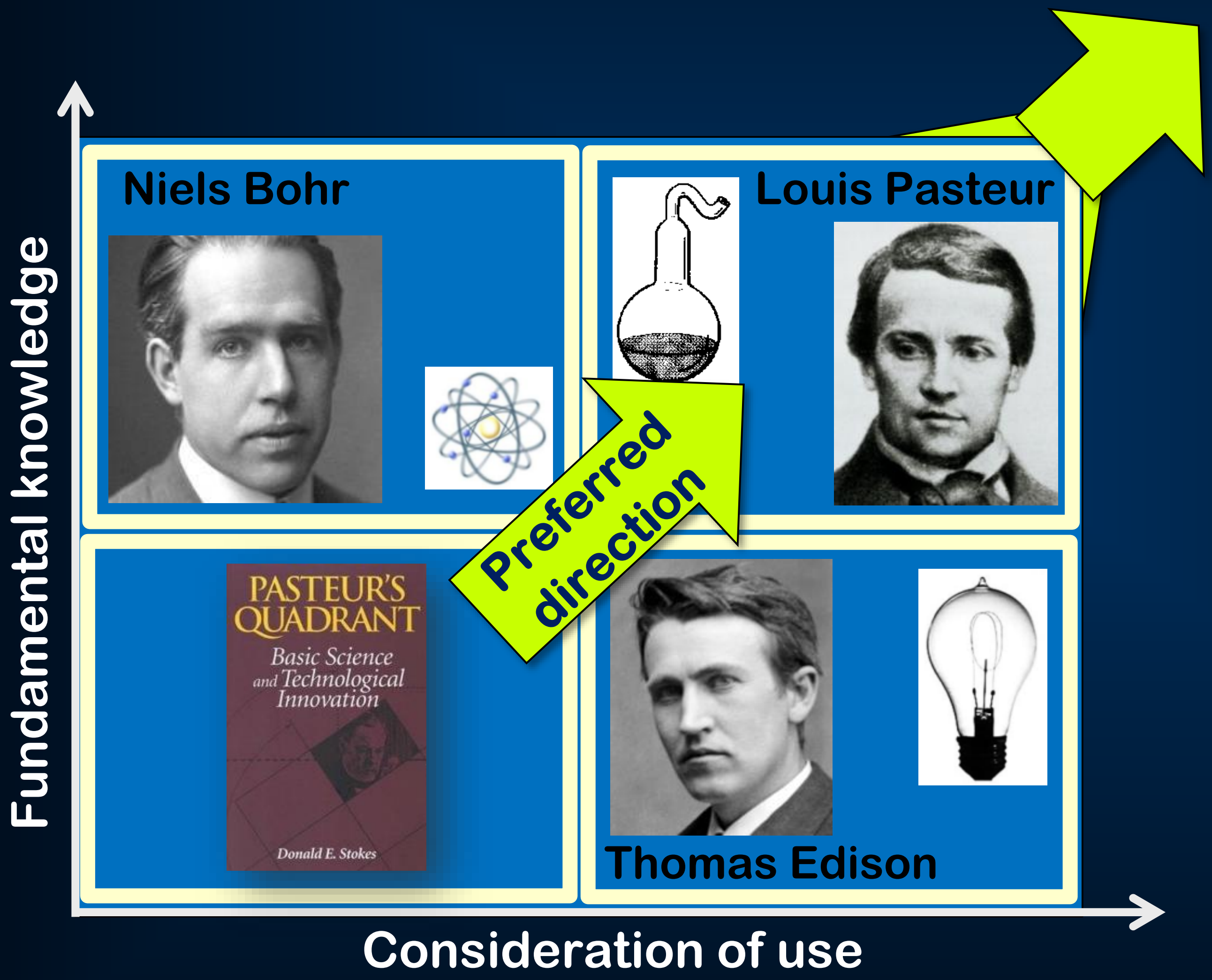
including those based on plasma acceleration

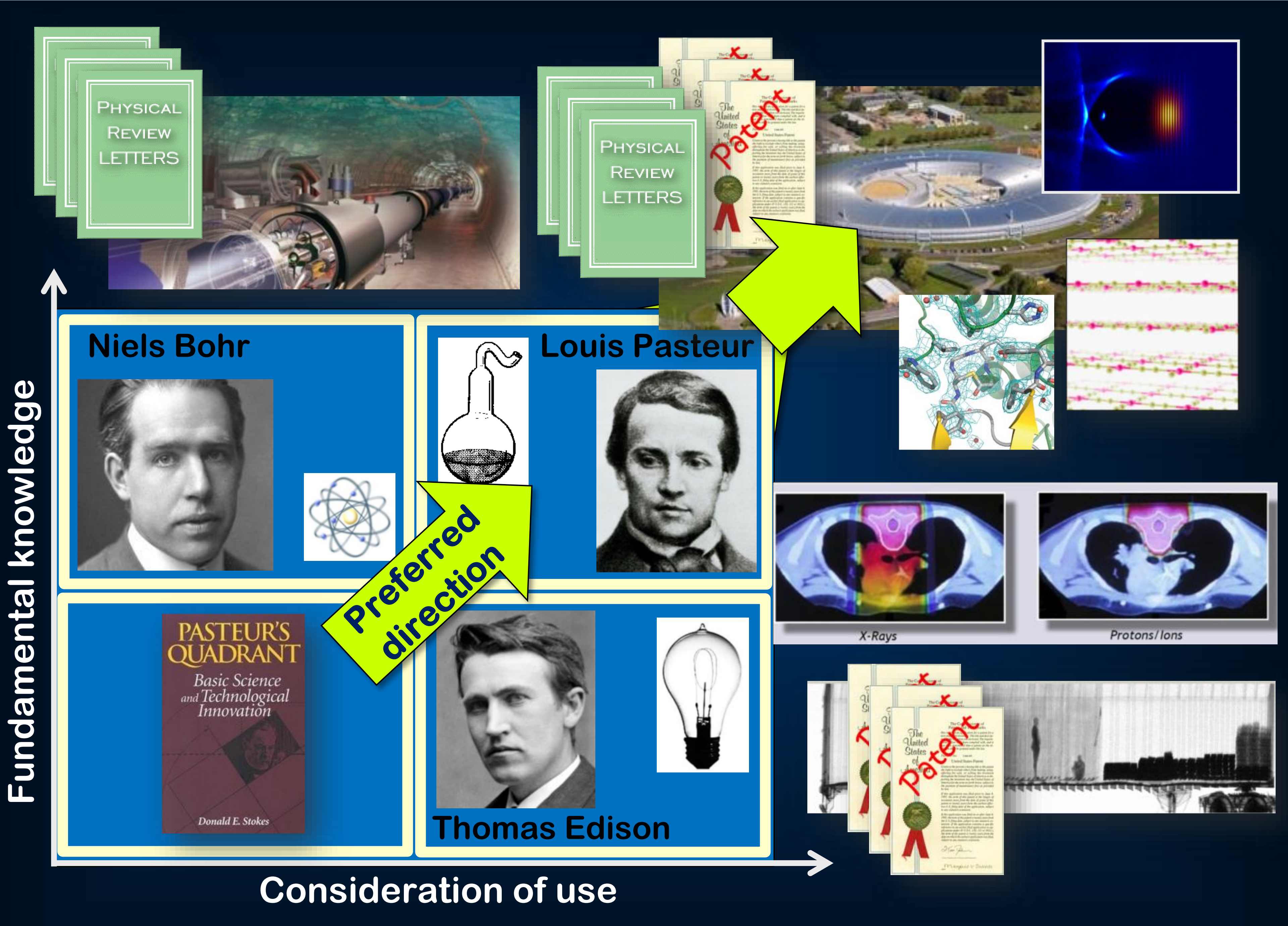
But first, let’s define some metric which allow us to evaluate and compare the importance of different directions of research

Why SR sources are so important?



Why SR sources are so important?

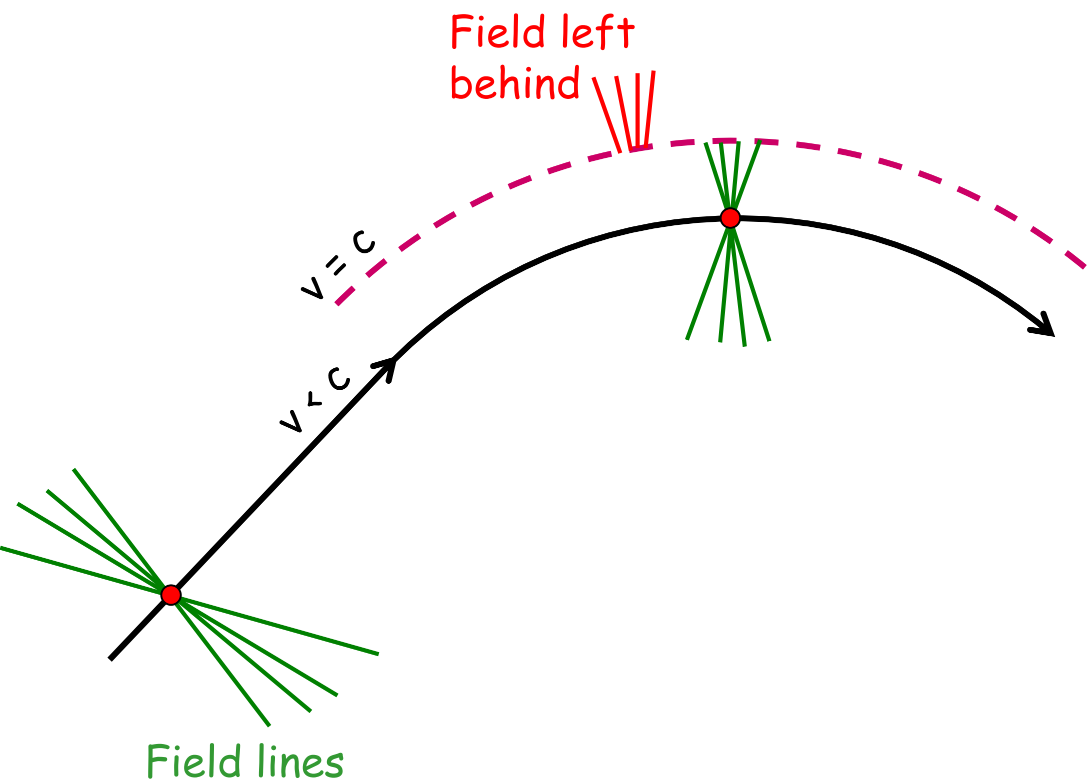



PHYSICAL REVIEW LETTERS
PHYSICAL REVIEW LETTERS
Patent
Niels Bohr
Louis Pasteur
Preferred direction
PASTEUR'S QUADRANT
Basic Science and Technological Innovation
Donald E. Stokes
Thomas Edison
X-Rays
Protons/Ions
Patent
Fundamental knowledge
Consideration of use

Synchrotron light source

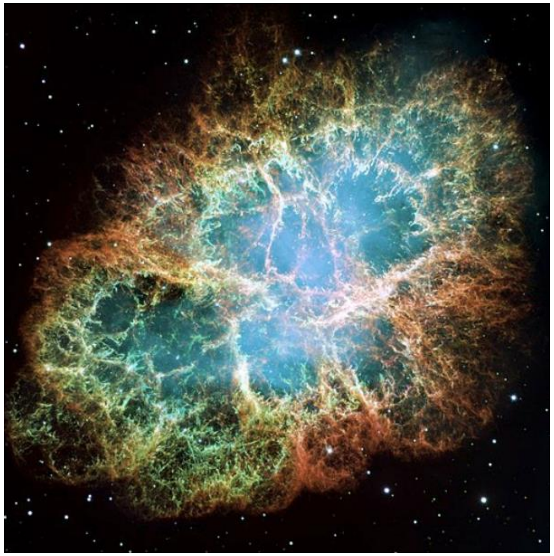
How does it work?

SR effects - qualitatively



- Simplistic picture – SR caused by leaving part of the fields behind
- Can be useful as it
  - Creates high brightness radiation source
- Can be harmful as it
  - Creates additional energy spread
  - Creates additional emittance growth

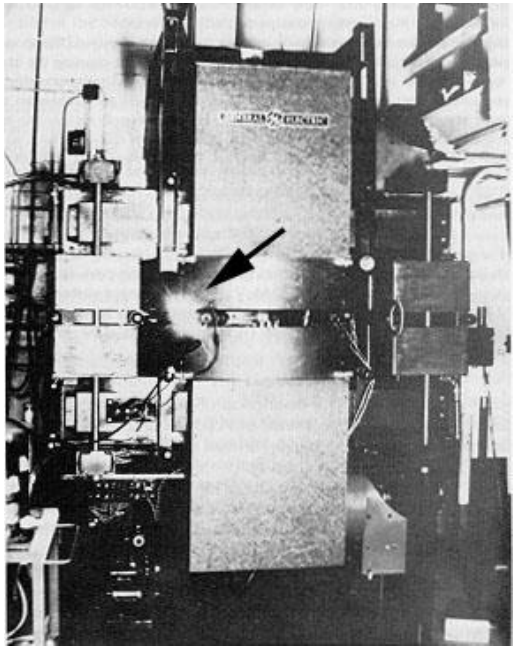
968 years of Synchrotron Radiation observation



Crab Nebula is supernova remnant corresponds to a bright supernova recorded in 1054

凡十一日沒三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅大星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁沒明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日沒至和元年五月己丑出天關東南可數寸歲餘
稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守
宋史志卷九

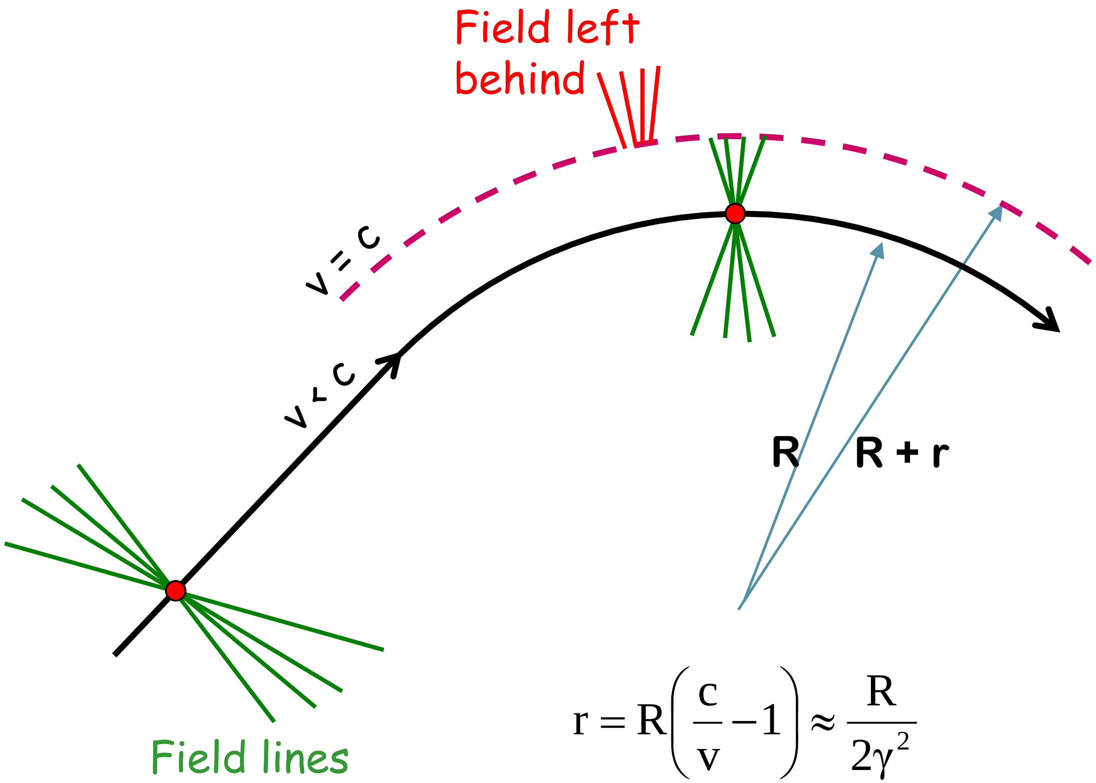
In 1054 Chinese and Japanese monks recorded story about bright guest star that was visible even day time for about three weeks



SR observed in 1947 in GE 70 MeV synchrotron

~900 years after the birth of Crab Nebula it was suggested that its blue region shining is caused by Synchrotron Radiation of relativistic electrons in magnetic field. This idea was later confirmed by observation and the source of magnetic field was determined to be a neutron star in the center of the nebula

Synchrotron radiation
on-the-back-of-the-envelope – power loss

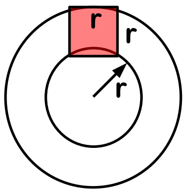


$$r = R\left(\frac{c}{v} - 1\right) \approx \frac{R}{2\gamma^2}$$

Energy in the field left behind (radiated !):

$$W \approx \int E^2\, dV$$

The field $E \approx \dfrac{e}{r^2}$ **the volume** $V \approx r^2\, dS$



Energy loss per unit length:

$$\frac{dW}{dS} \approx E^2 r^2 \approx \left(\frac{e}{r^2}\right)^2 r^2$$

Substitute $r \approx \dfrac{R}{2\gamma^2}$ **and get an estimate:**

$$\boxed{\frac{dW}{dS} \approx \frac{e^2\gamma^4}{R^2}}$$

Compare with exact formula: $\dfrac{dW}{dS} = \dfrac{2}{3}\dfrac{e^2\gamma^4}{R^2}$

Gaussian units on this page!

Re-inventing the way to increase LEP energy

LEP was e+e- machine, and around 2000 was running with the energy about 104 GeV per beam

The energy was limited by energy losses due to synchrotron radiation, and by the amount of voltage from the installed RF cavities

LEP optical structure include all typical magnets: bending dipoles, quadrupoles with corrector coils, sextupoles.

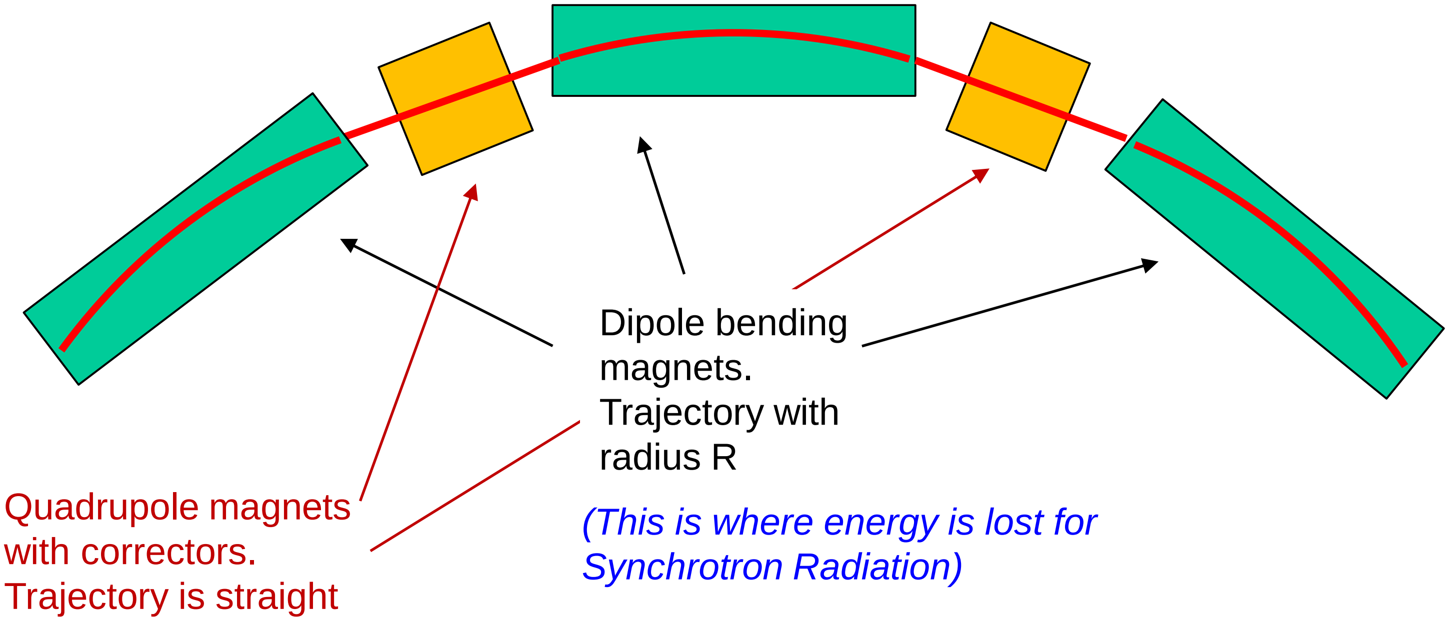
Assume you cannot install more RF to compensate for SR energy losses

How can you increase LEP energy?

(Without moving the vacuum chamber or magnets).

Hint: Try to use resources that you already have in the system

Re-inventing the way to increase LEP energy

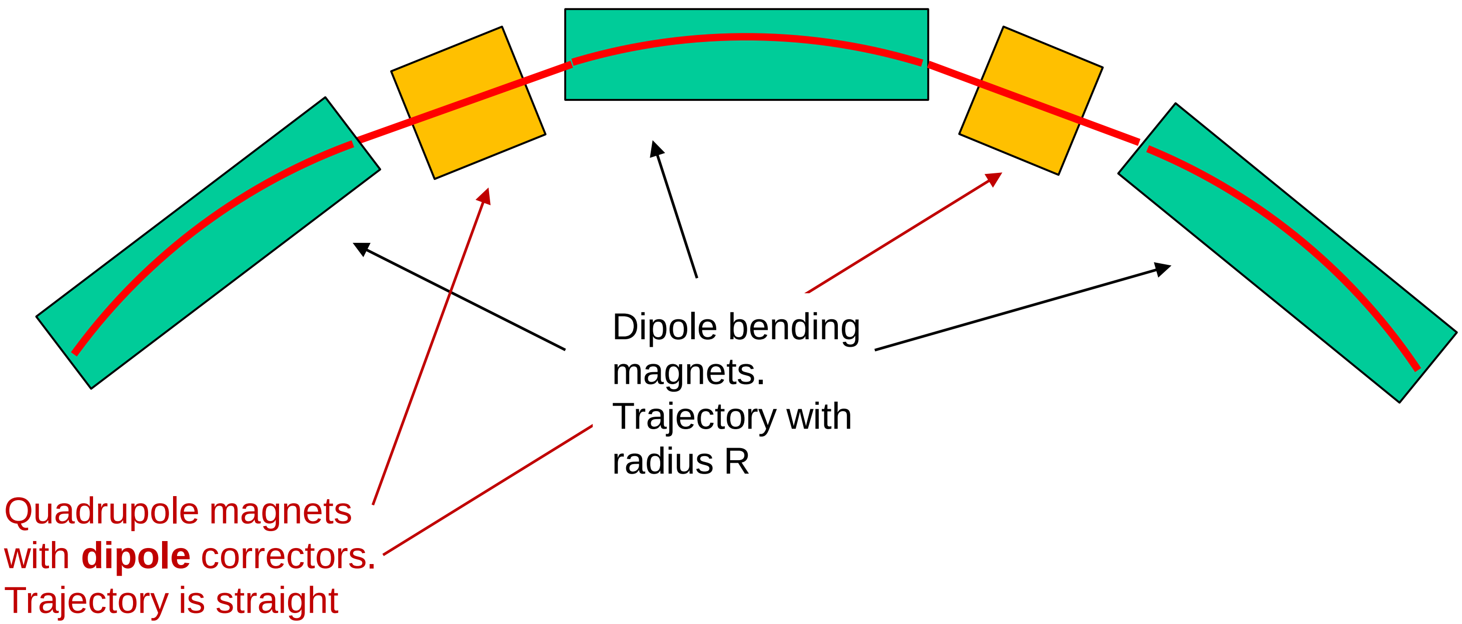


(This is where energy is lost for Synchrotron Radiation)

How can you increase LEP energy?

Try to use resources that you already have in the system

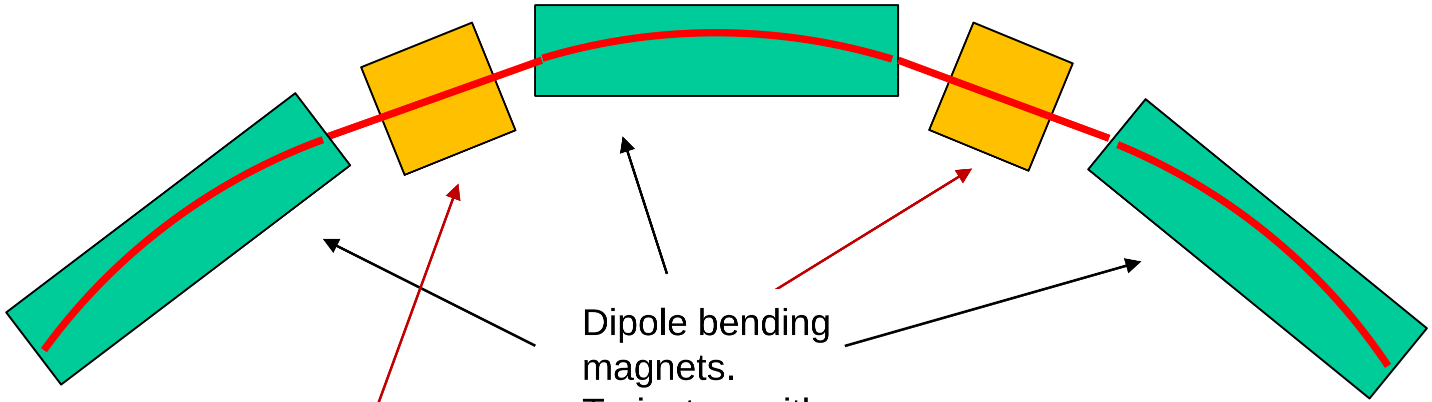
Re-inventing the way to increase LEP energy



How can you increase LEP energy?

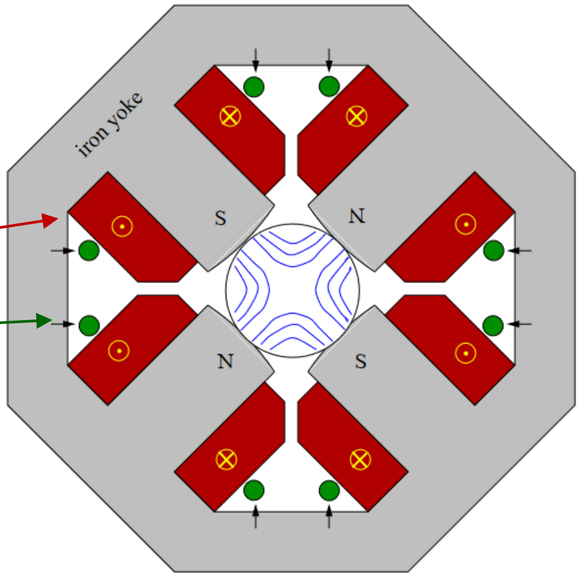
Try to use resources that you already have in the system

Re-inventing the way to increase LEP energy



Dipole bending magnets. Trajectory with radius R

Quadrupole magnets with **dipole** correctors. Trajectory is straight



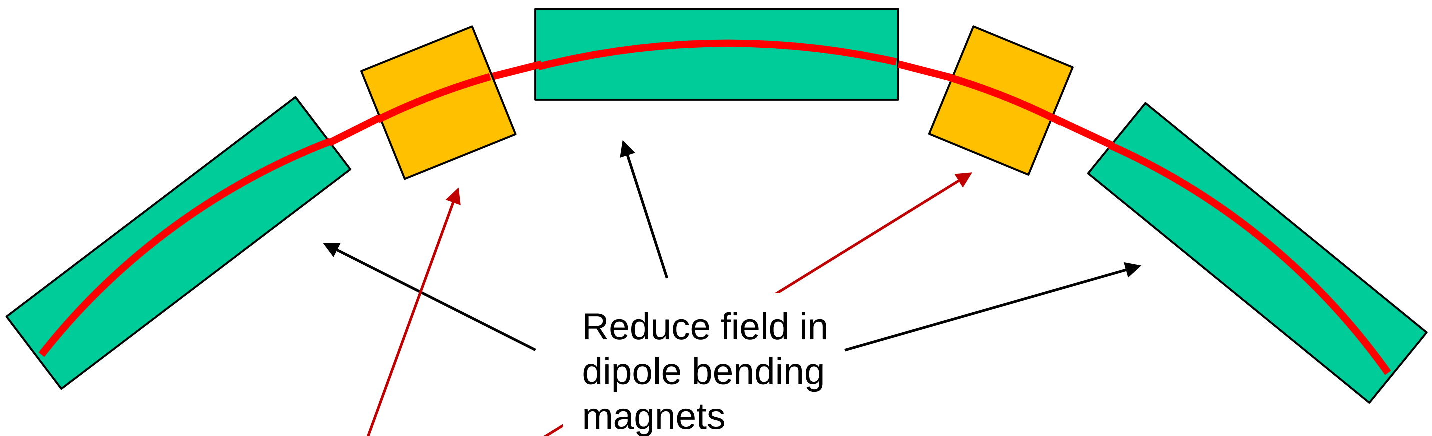
LEP quadrupole Main winding

Correctors windings can be powered separately and can provide dipole correction

How can you increase LEP energy?

Try to use resources that you already have in the system

Re-inventing the way to increase LEP energy



Power up dipole correctors in Quadrupoles so that trajectory become slightly **curved**

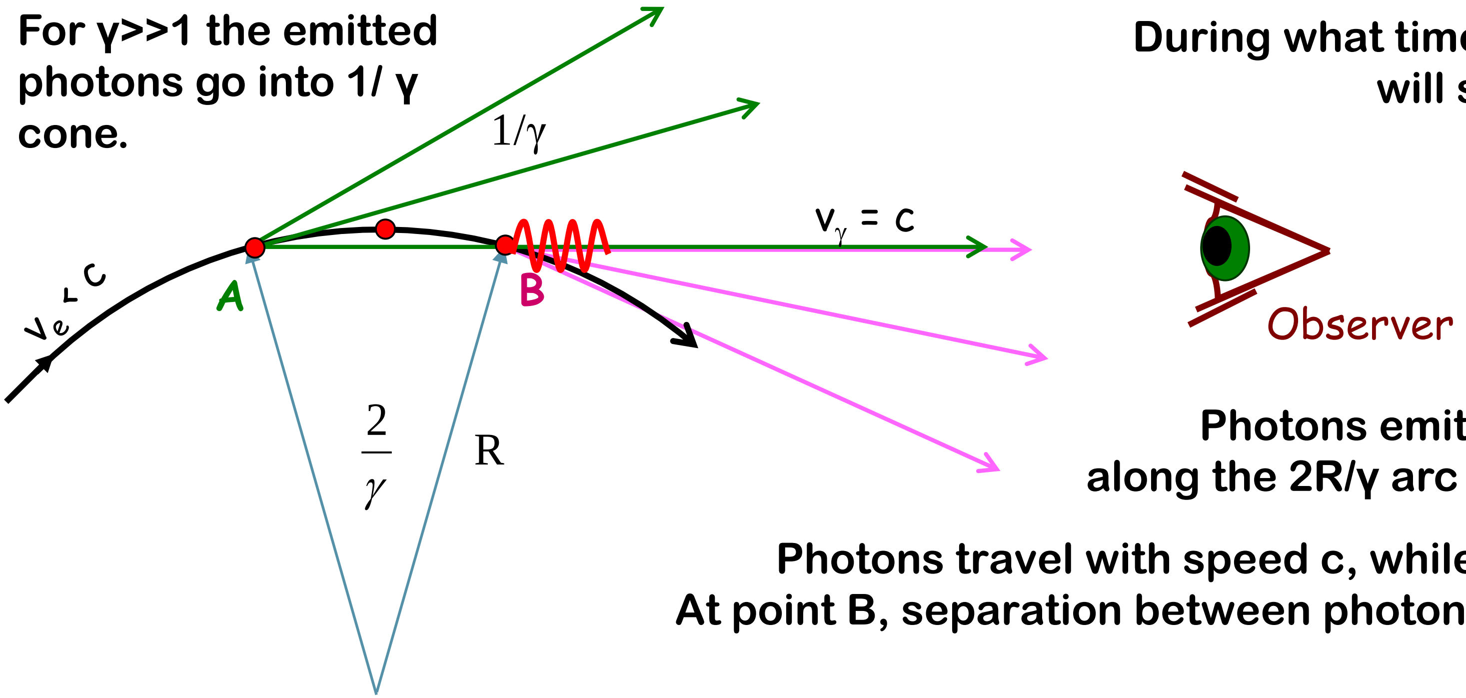
This will make the trajectory more smooth, and will decrease energy loss due to Synchrotron Radiation

This allowed to increase LEP energy by a fraction of a GeV

Increasing the LEP energy for a given RF voltage, P.Raimondi https://cds.cern.ch/record/398739/files/open-99-125.pdf
Proposal to Increase the LEP Energy with Horizontal Orbit Correctors, A. Beuret, S. Bidon, G. de Rijk, R. Genand, P. Raimondi, J.Wenninger, https://jwenning.web.cern.ch/documents/EnergyCal/chramp.pdf

Synchrotron radiation
on-the-back-of-the envelope – photon energy

For γ>>1 the emitted photons go into 1/ γ cone.



During what time Δt the observer will see the photons?

Photons emitted during travel along the 2R/γ arc will be observed.

Photons travel with speed c, while particles with v. At point B, separation between photons and particles is

$$dS \approx \frac{2R}{\gamma}\left(1-\frac{v}{c}\right)$$

Therefore, observer will see photons during $\Delta t \approx \frac{dS}{c} \approx \frac{2R}{c\gamma}(1-\beta) \approx \frac{R}{c\gamma^3}$

Estimation of characteristic frequency

$$\boxed{\omega_c \approx \frac{1}{\Delta t} \approx \frac{c\gamma^3}{R}}$$

Compare with exact formula:

$$\omega_c = \frac{3}{2}\frac{c\gamma^3}{R}$$

Synchrotron radiation *on-the-back-of-the envelope* – number of photons

We estimated the rate of energy loss: $\frac{dW}{dS} \approx \frac{e^2 \gamma^4}{R^2}$ **And the characteristic frequency:** $\omega_c \approx \frac{c\gamma^3}{R}$

&

The photon energy $\varepsilon_c = \hbar\omega_c \approx \frac{\gamma^3 \hbar c}{R} = \frac{\gamma^3}{R} \lambda_e mc^2$ **where** $r_e = \frac{e^2}{mc^2}$ $\alpha = \frac{e^2}{\hbar c}$ $\lambda_e = \frac{r_e}{\alpha}$

=>

Number of photons emitted per unit length $\frac{dN}{dS} \approx \frac{1}{\varepsilon_c}\frac{dW}{dS} \approx \frac{\alpha\gamma}{R}$ **(per angle** θ**:** $N \approx \alpha\gamma\theta$ **)**

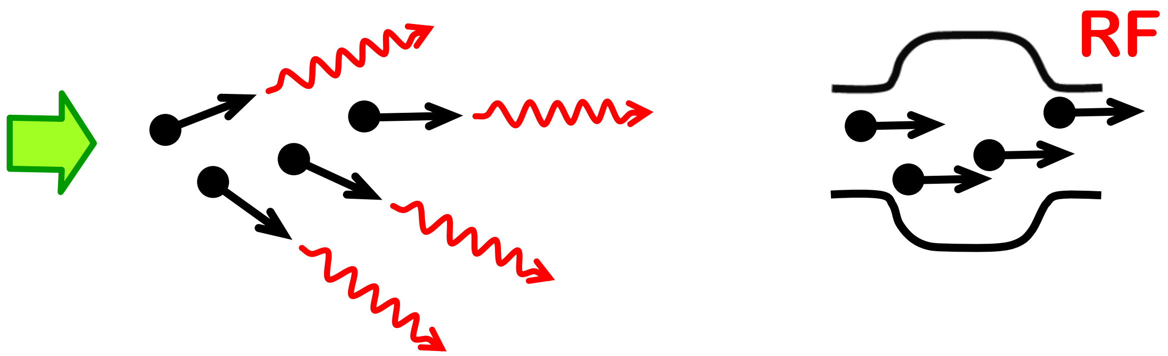
Gaussian units on this page!

Let's estimate cooling time

We estimated that losses per unit length are: $\frac{dW}{dS} = \frac{2}{3}\frac{e^2\gamma^4}{R^2}$ or $\frac{dW}{dS} = \frac{2}{3}\frac{r_e\,\gamma^4}{R^2}mc^2$

Thus losses per turn are: $U_0 = \frac{4\pi}{3}\frac{r_e\,\gamma^4}{R}mc^2$

When electron radiate a photon, its momentum decrease



RF cavity restores only longitudinal momentum, thus other degrees of freedom cooled

Estimate cooling time τ as E_0T_0/U_0: $\tau \approx \frac{2\pi R}{c}\frac{\gamma mc^2}{U_0}$ or $\tau^{-1} \approx \frac{2}{3}\frac{c\,r_e\,\gamma^3}{R^2}$

Equilibrium emittance

- Have SR cooling – would beam emittance reduce to zero?

- No, as there are quantum fluctuations

- Let's make simple estimations of the effects

Let's estimate energy spread growth due to SR

We estimated the rate of energy loss: $\frac{dW}{dS} \approx \frac{e^2 \gamma^4}{R^2}$ And the characteristic frequency: $\omega_c \approx \frac{c\gamma^3}{R}$

The photon energy $\varepsilon_c = \hbar\omega_c \approx \frac{\gamma^3 \hbar c}{R} = \frac{\gamma^3}{R}\lambda_e mc^2$ where $r_e = \frac{e^2}{mc^2}$ $\alpha = \frac{e^2}{\hbar c}$ $\lambda_e = \frac{r_e}{\alpha}$

Number of photons emitted per unit length $\frac{dN}{dS} \approx \frac{1}{\varepsilon_c}\frac{dW}{dS} \approx \frac{\alpha\gamma}{R}$ (per angle θ: $N \approx \alpha\gamma\theta$)

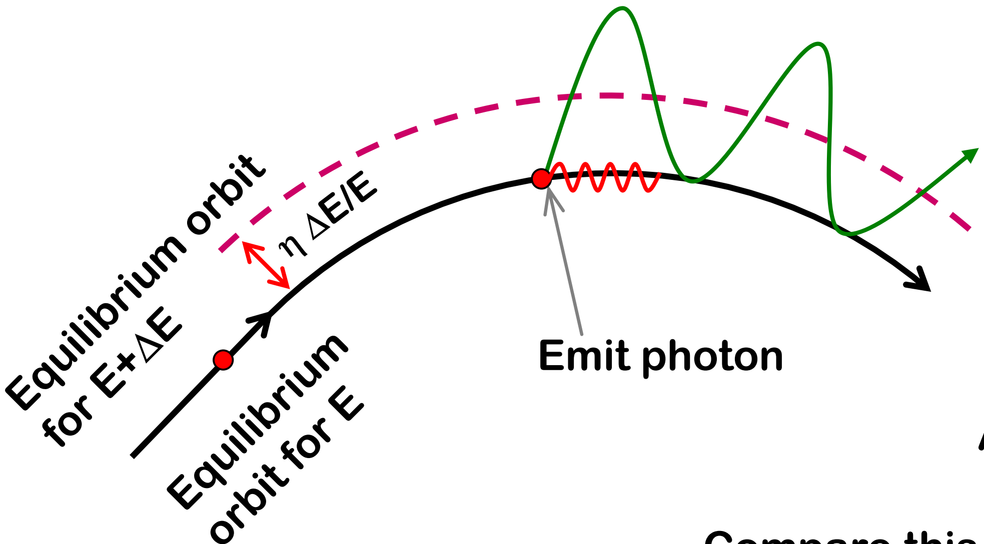
The energy spread ΔE/E will grow due to statistical fluctuations ($\sqrt{N}$) of the number of emitted photons :

$$\frac{d\left((\Delta E/E)^2\right)}{dS} \approx \varepsilon_c^2 \frac{dN}{dS}\frac{1}{\left(\gamma mc^2\right)^2}$$

Which gives: $\boxed{\frac{d\left((\Delta E/E)^2\right)}{dS} \approx \frac{r_e \lambda_e \gamma^5}{R^3}}$

Compare with exact formula: $\frac{d\left((\Delta E/E)^2\right)}{dS} = \frac{55}{24\sqrt{3}}\frac{r_e \lambda_e \gamma^5}{R^3}$

Let's estimate emittance growth rate due to SR



Dispersion function η shows how equilibrium orbit shifts when energy changes

When a photon is emitted, the particle starts to oscillate around new equilibrium orbit

Amplitude of oscillation is $\Delta x \approx \eta\, \Delta E/E$

Compare this with betatron beam size: $\sigma_x = (\varepsilon_x\, \beta_x)^{1/2}$

And write emittance growth: $\Delta\varepsilon_x \approx \dfrac{\Delta x^2}{\beta}$

Resulting estimation for emittance growth:

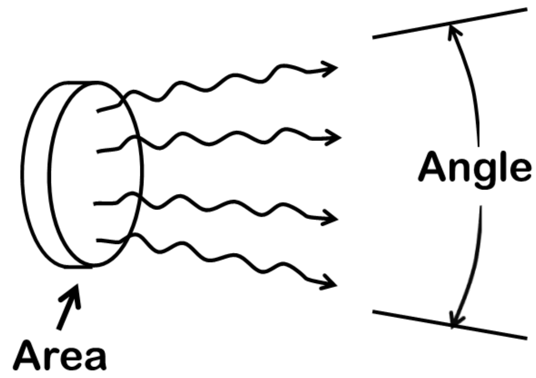
$$\frac{d\varepsilon_x}{dS} \approx \frac{\eta^2}{\beta_x} \frac{d\left((\Delta E/E)^2\right)}{dS} \approx \boxed{\frac{\eta^2}{\beta_x} \frac{r_e\, \lambda_e\, \gamma^5}{R^3}}$$

Compare with exact formula (which also takes into account the derivatives):

$$\frac{d\varepsilon_x}{dS} = \underbrace{\boxed{\frac{\left(\eta^2 + (\beta_x \eta' - \beta'_x \eta/2)^2\right)}{\beta_x}}}_{=\mathcal{H}} \frac{55}{24\sqrt{3}} \frac{r_e\, \lambda_e\, \gamma^5}{R^3}$$

Brightness

- Brightness of synchrotron light sources



Brightness
photons / (s m^2 rad^2 (%bandwidth))

- How we can increase brightness
  - Smaller size of emitting area
  - Smaller angular divergence
- I.e. decrease equilibrium emittance

Equilibrium emittance due to SR

Estimation for emittance growth:

$$\frac{d\varepsilon_x}{dS} \approx \frac{\eta^2}{\beta_x} \frac{d\left(\left(\Delta E/E\right)^2\right)}{dS} \approx \boxed{\frac{\eta^2}{\beta_x} \frac{r_e \lambda_e \gamma^5}{R^3}}$$

Exact formula takes into account the derivatives:

$$\frac{d\varepsilon_x}{dS} = \underbrace{\boxed{\frac{\left(\eta^2 + \left(\beta_x \eta' - \beta'_x \eta /2\right)^2\right)}{\beta_x}}}_{=\mathcal{H}} \frac{55}{24\sqrt{3}} \frac{r_e \lambda_e \gamma^5}{R^3}$$

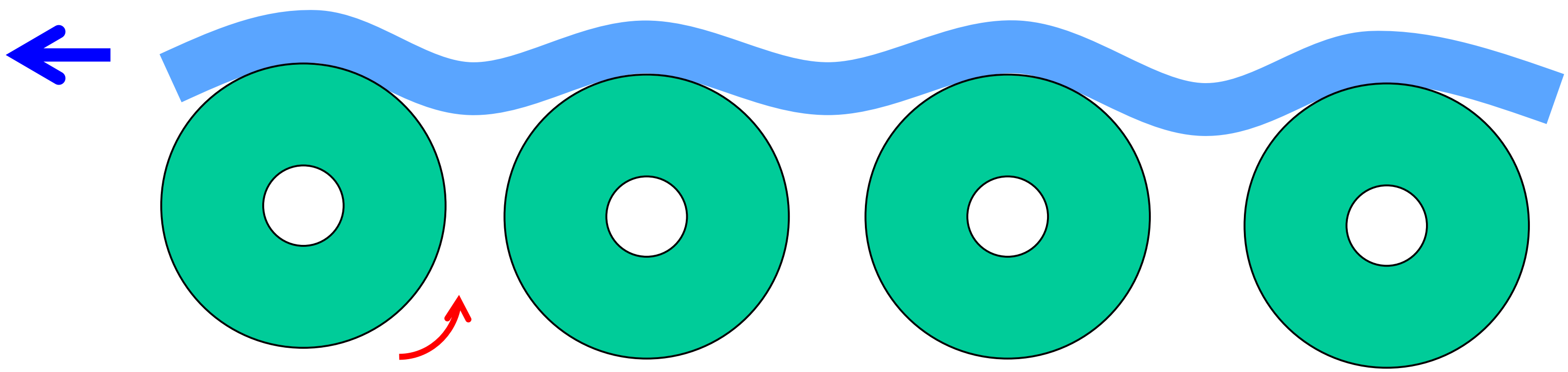
SR cooling gives $\frac{d\varepsilon}{ds} = -\frac{2}{c\tau}\varepsilon$ **with** $\tau^{-1} = \frac{1}{3}\frac{c\, r_e \gamma^3}{R^2}$

The equilibrium emittance will therefore be proportional to the average value of the ***curly*** $\mathcal{H}$ function

If we can minimize the average value of $\mathcal{H}$ for a regular optical cell of SR light source, we can reduce beam emittance and thus increase brightness

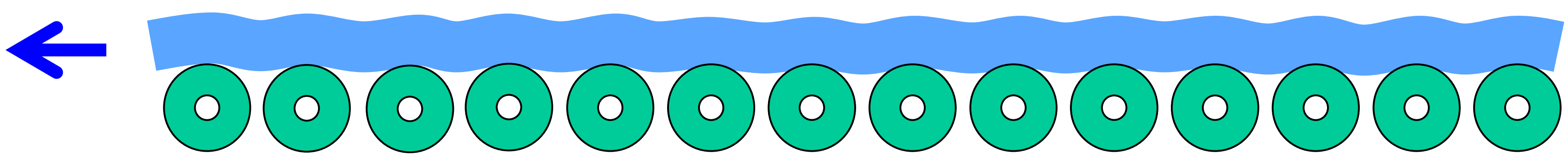
Inventing a better conveyor for glass manufacturing

Need to transport hot glass, just of the oven, on a conveyor



Large rollers of the conveyor cause deformation of glass, impact quality

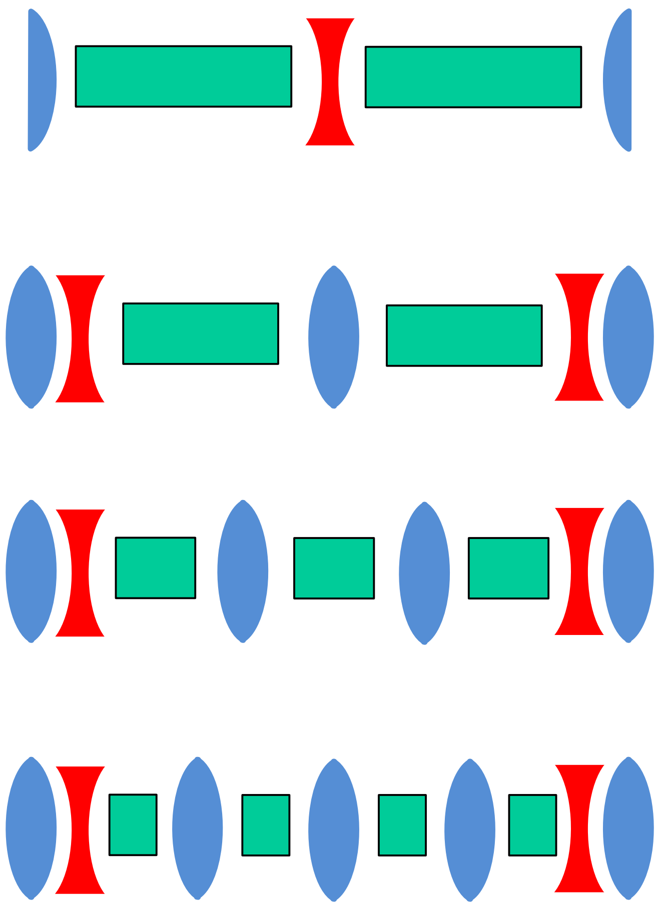
To improve quality, one can make rollers smaller, and use more of them



But this increase the cost of the conveyor

How to improve glass quality without increasing cost?

Evolution of types of SR sources optics sells

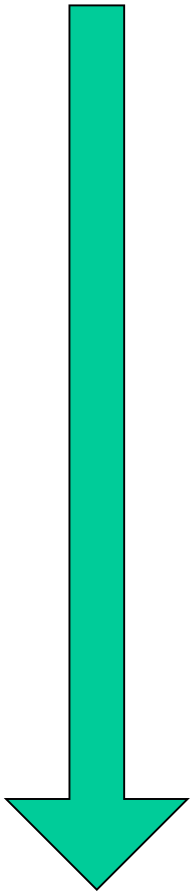


FODO with two bends

DBA – double bend achromat

TBA – triple bend achromat

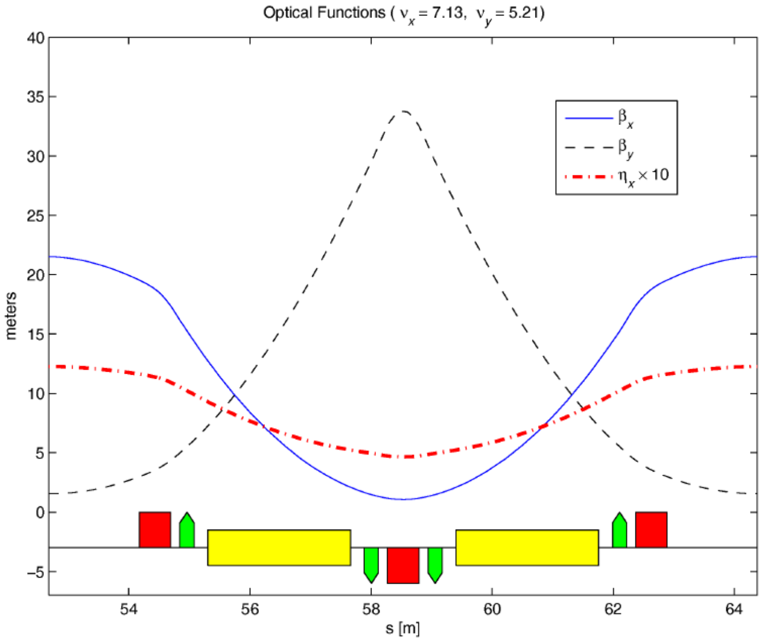
MBA – multi bend achromat



Equilibrium emittance is decreasing from top to bottom

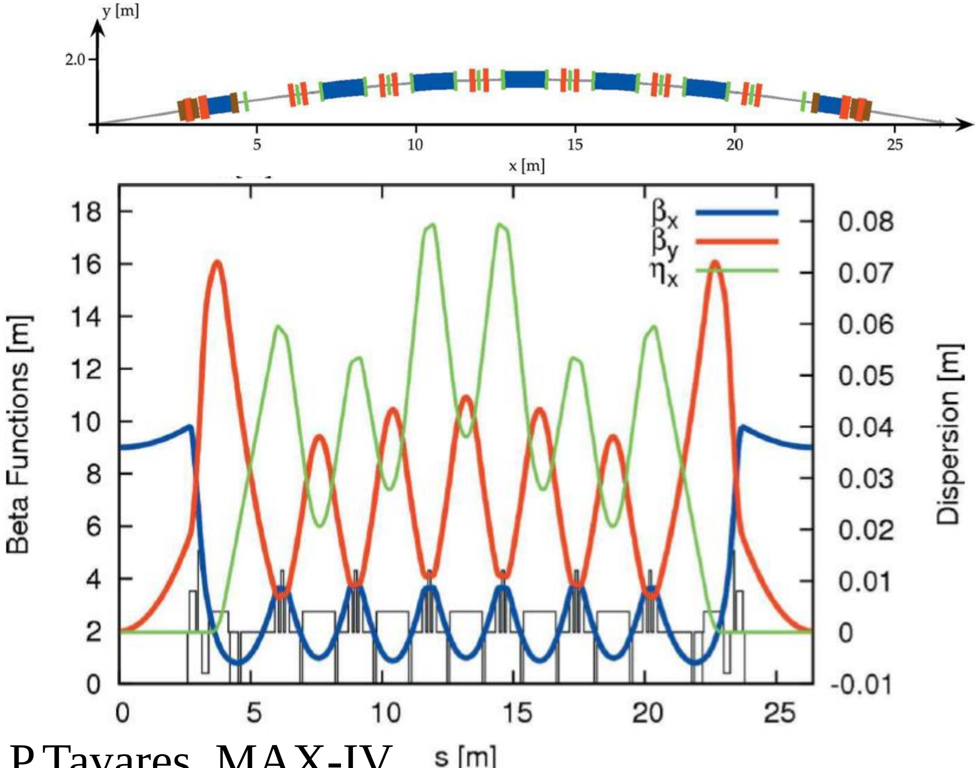
Examples of FODO and MBA optics

SPEAR-2 FODO



K.Wootton, SLAC

MAX-IV MBA (seven bend achromat)



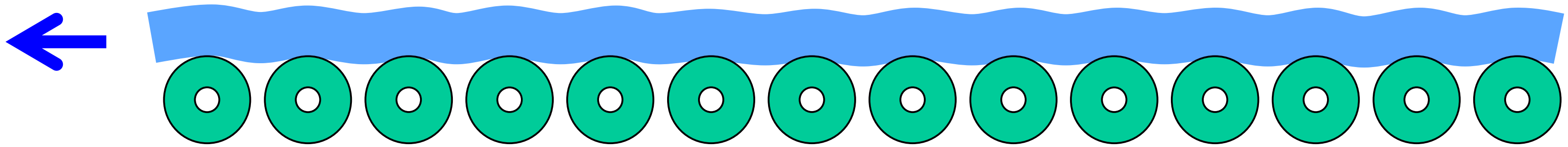
P.Tavares, MAX-IV

Evolution from FODO to MBA – increase number of bends in cell, better optimization of optics, minimize emittance, maximize brightness

Is it possible to improve it further?

Inventing a better conveyor for glass manufacturing

To improve quality, one can make rollers smaller, and use more of them

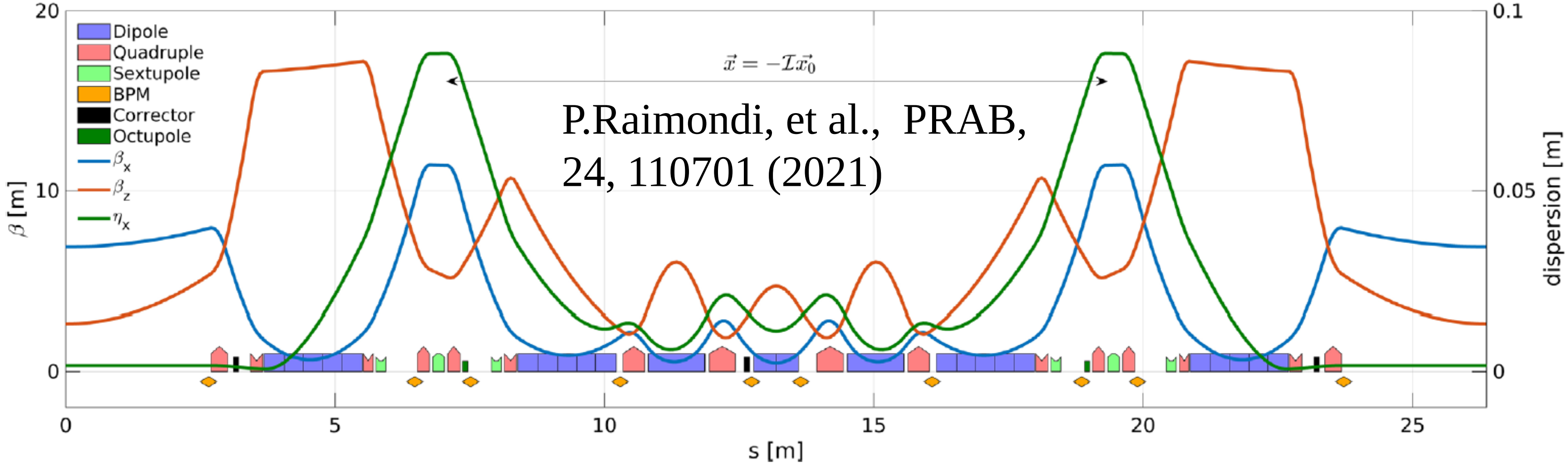


For maximum glass quality the rollers needs to be of zero size.
They should be atom size!
Use metal with low T of melting
E.g. liquid tin

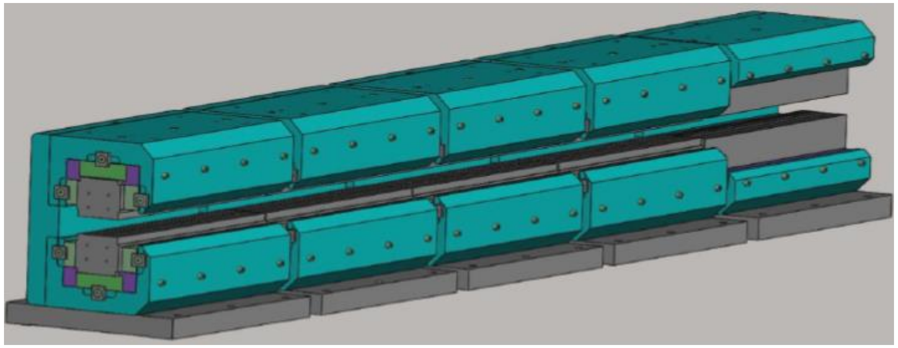
Liquid tin conveyor

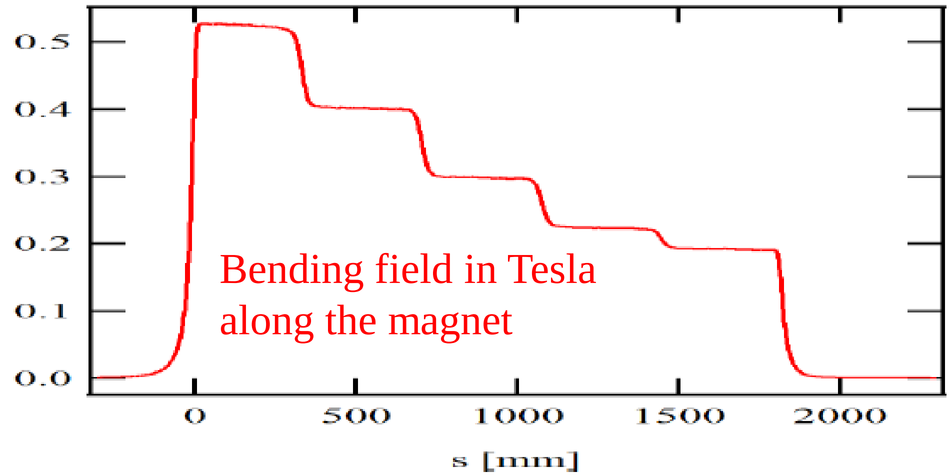
From MBA to Hybrid Multi Bend Achromat

ESRF-EBS HMBA



Instead of going to even larger number of bends, HMBA use bending magnets with field varying along the magnet, for better optimization of optics

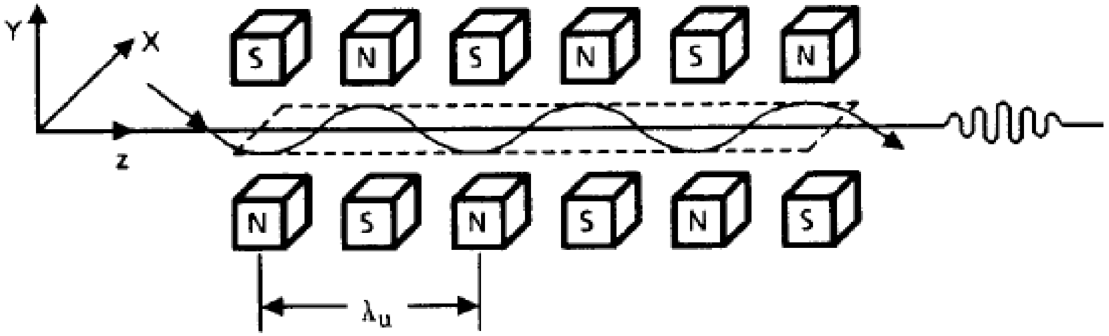




How to increase brightness - undulators & wigglers

Periodic array of magnetic poles providing a sinusoidal magnetic field on axis:

$$B = (0, \quad B_0 \sin(k_u z), \quad 0,)$$

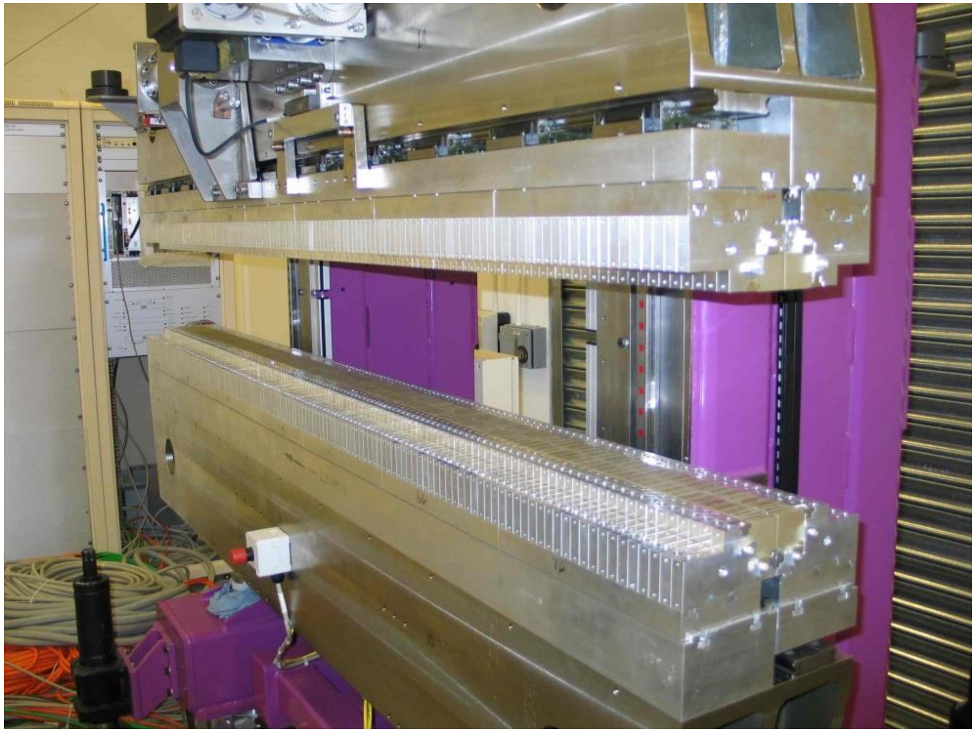


Insertion devices (undulators) to generate high brilliance radiation

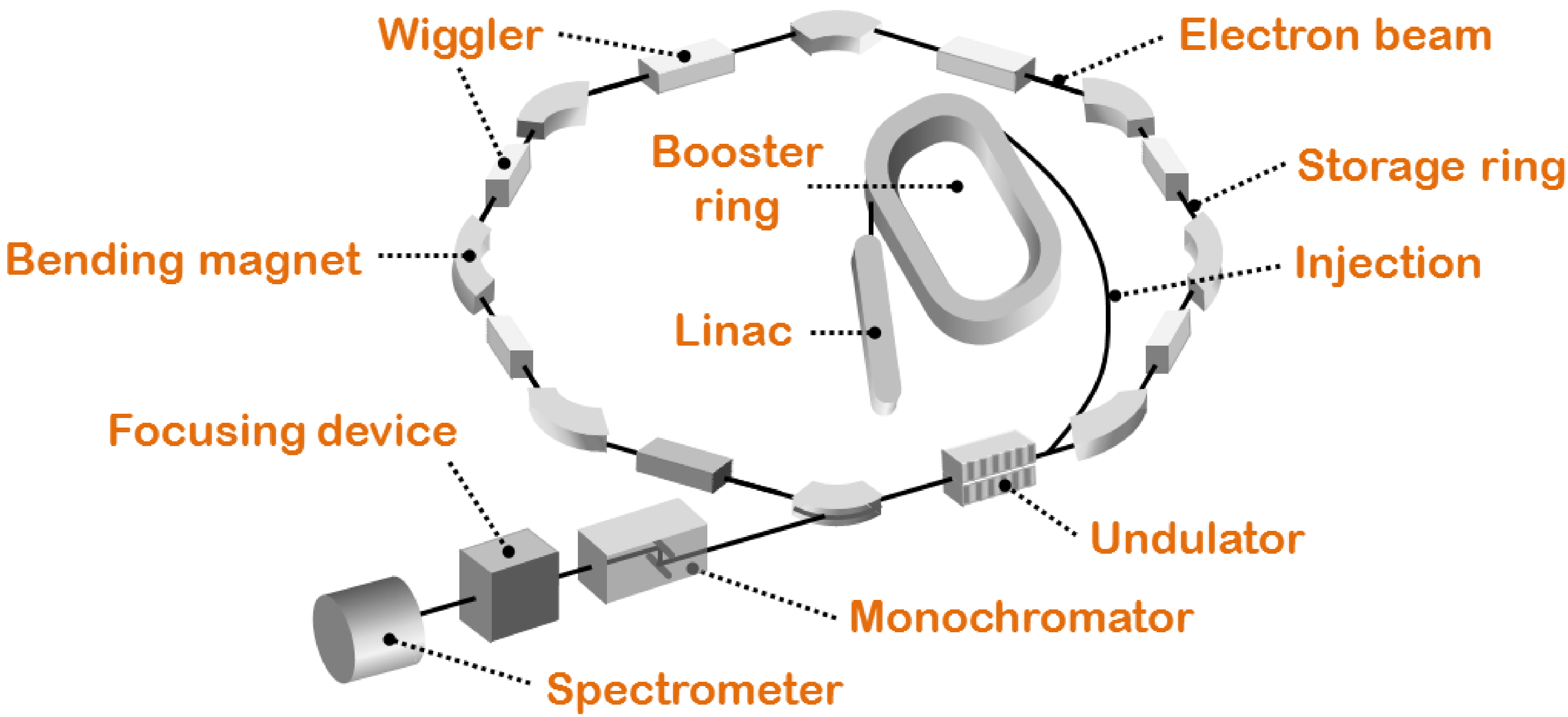
ID gap can be adjustable

Some ID are in-vacuum devices

Some in-vacuum ID can be open during injection and closed only when beam emittance reduced

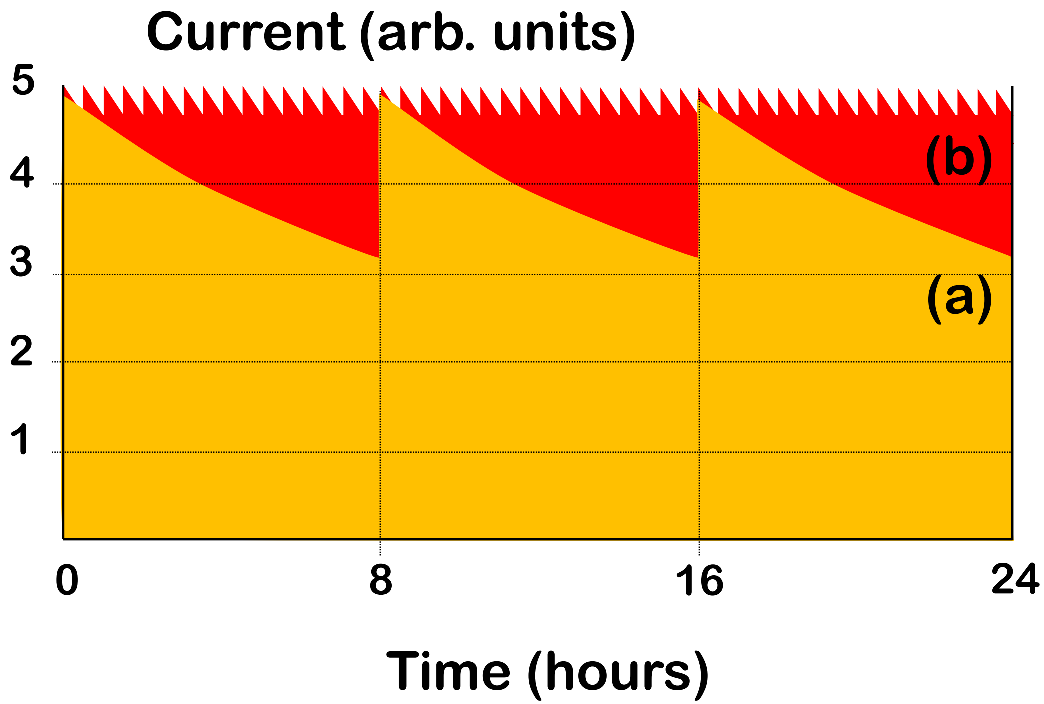


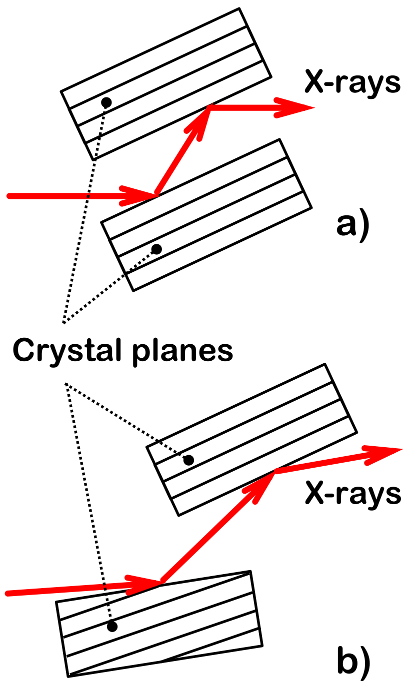
Layout of a synchrotron radiation source (II)



Synchrotron storage ring

T stability ; Monochromators

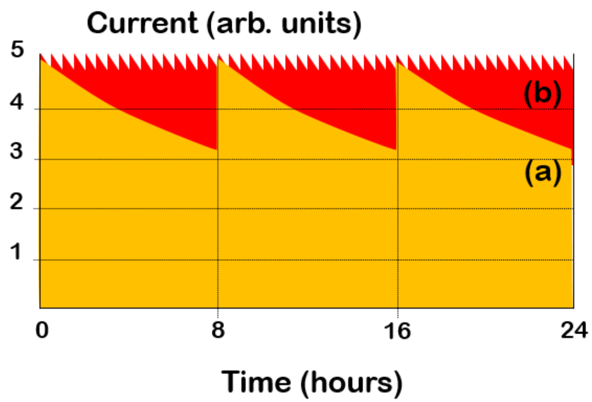


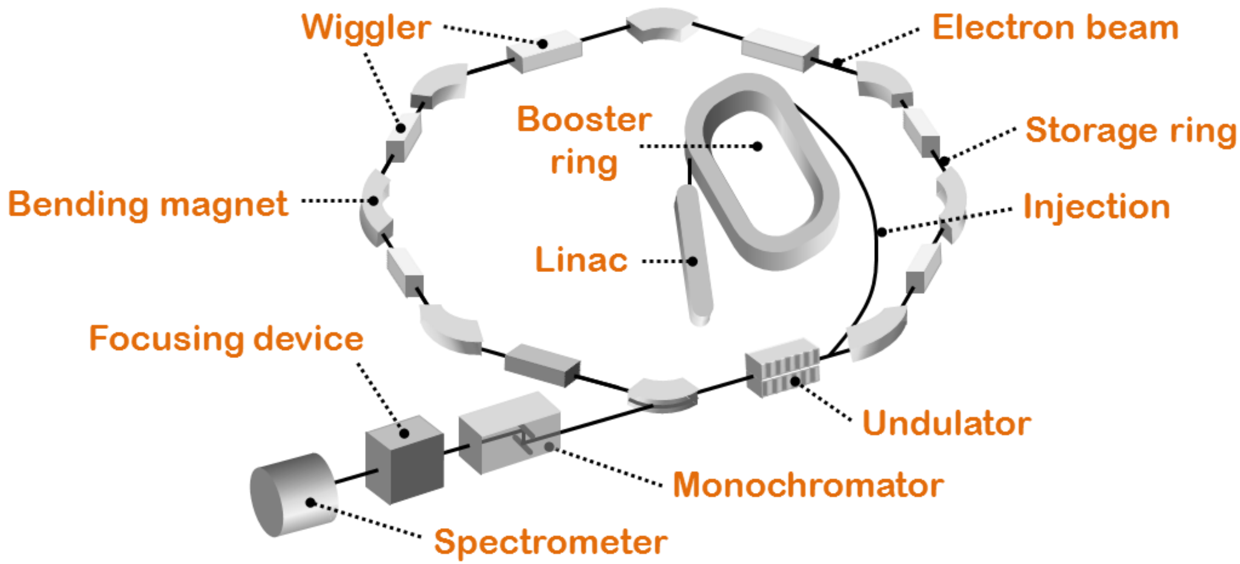


Top-up injection

Use crystals and Bragg condition

Re-inventing injection to SR sources





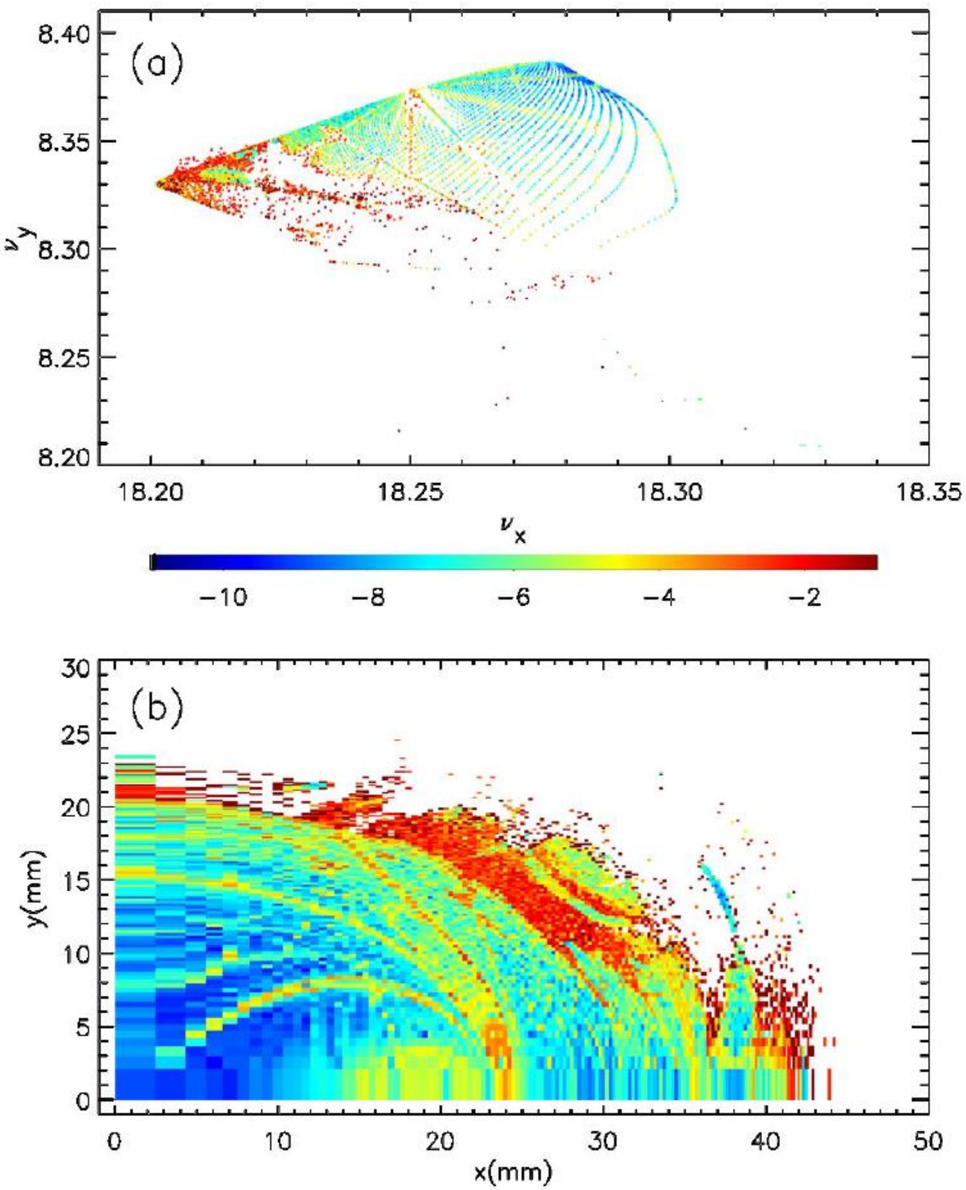
- Top-up injection advantages:
  - No issue with beam lifetime
  - Stable temperature conditions to X-ray optics
- Top-up injection challenges:
  - Injection with shutters open
  - Injection with ID gaps closed
  - Dynamic aperture

SR sources and Dynamic Aperture

Tight focusing intended to reduce ***curly*** $\mathcal{H}$ – needs for stronger sextupoles

Sextupoles and insertion devices impact Dynamic Aperture (DA)

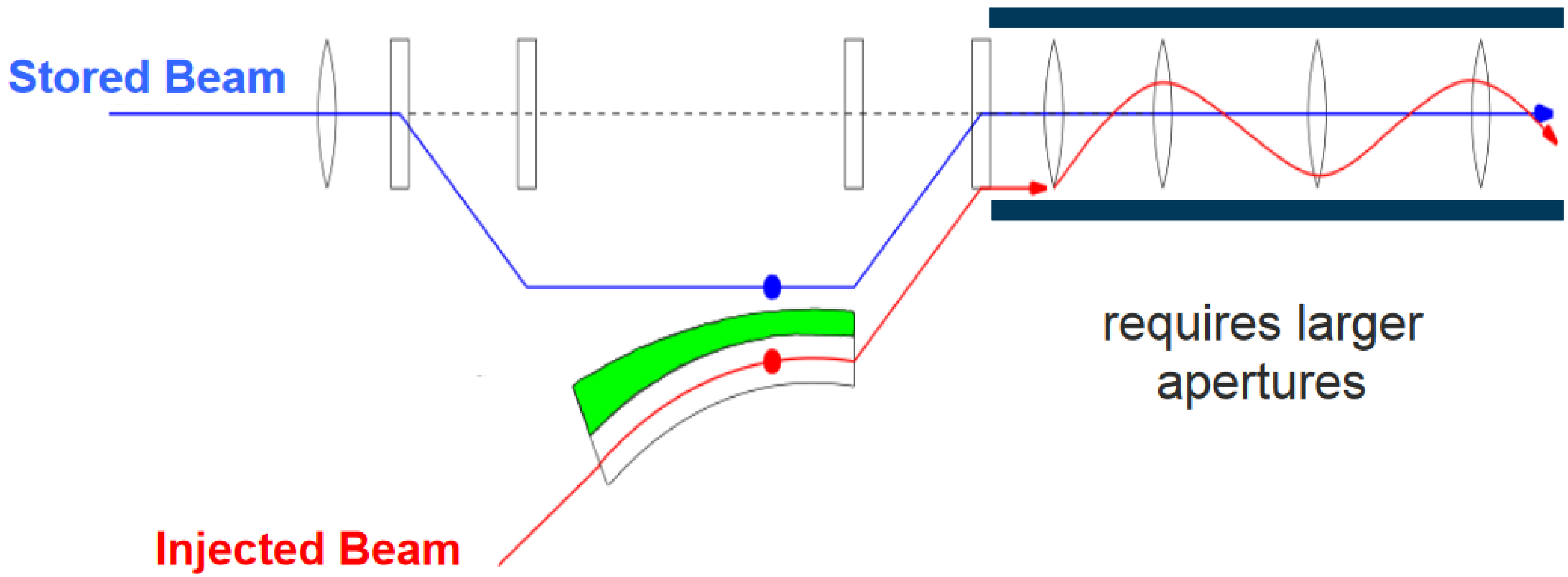
If the DA is small, it will affect injection efficiency and lifetime



Frequency Map (top) and DA (bottom)

L. Nadolski DOI: 10.1103/PhysRevSTAB.6.114801

Re-inventing injection to SR sources

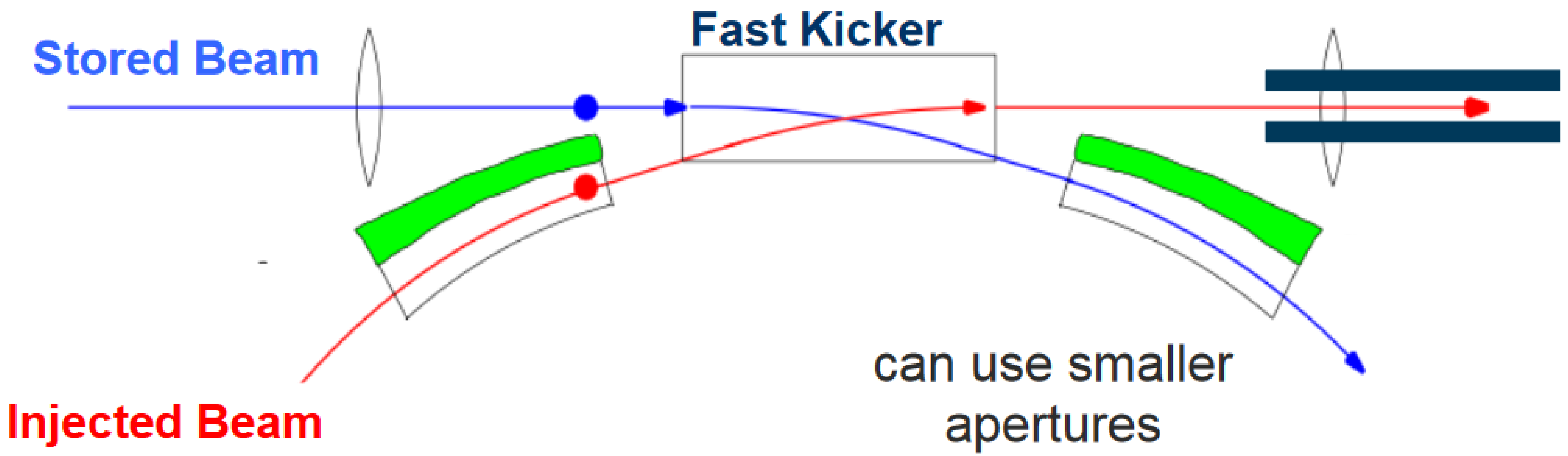


- For traditional off-axis injection (shown above) the injected bunch is oscillating until damped by SR
- If DA is not sufficiently large → beam losses, reduction of injection efficiency

How can we improve this situation? (How to inject efficiently into small DA?)

ALS-U – Robin - https://indico.bnl.gov/event/2938/contributions/7807/attachments/6991/8563/004_Robin_ALS-U.pdf

Re-inventing injection to SR sources



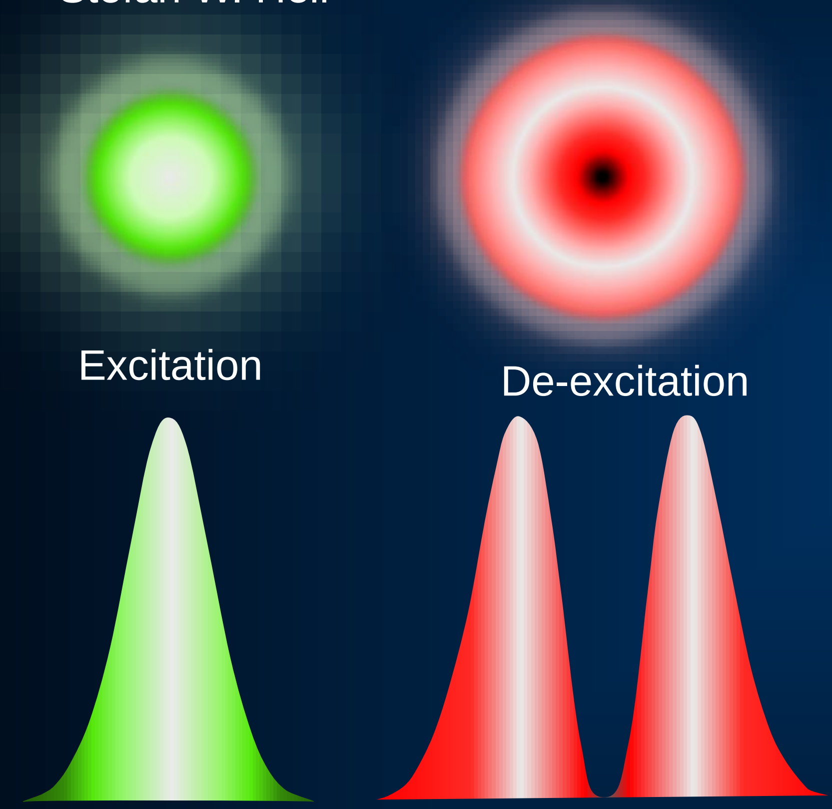
- For **on-axis swap-out injection** (shown above, M.Borland) the injected bunch is replacing one of circulating bunches almost without further oscillation
- Stronger focusing optics is possible
- Fast kicker is needed (usually strip-line design)

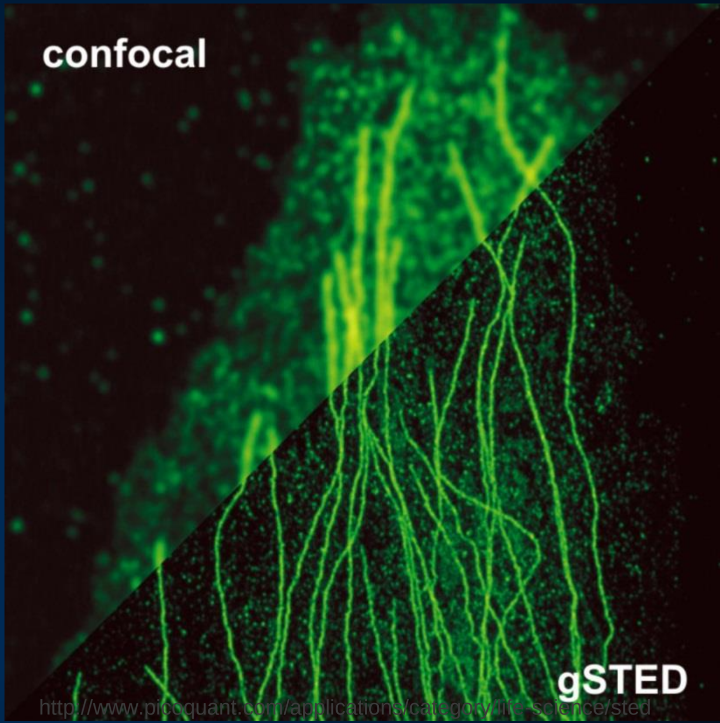
Are there other ways to improve injection into small DA?

ALS-U – Robin - https://indico.bnl.gov/event/2938/contributions/7807/attachments/6991/8563/004_Robin_ALS-U.pdf

Recall system anti-system & nested dolls

Stimulated Emission Depletion microscopy (STED)
Stefan W. Hell





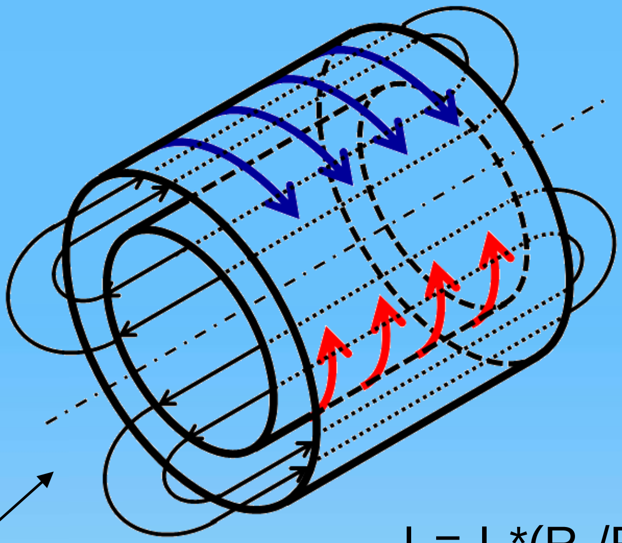
(gated) STED image of Tubulin vs standard confocal image

This can be viewed as a combination of the inventive principles “system and anti-system” and “nested dolls”

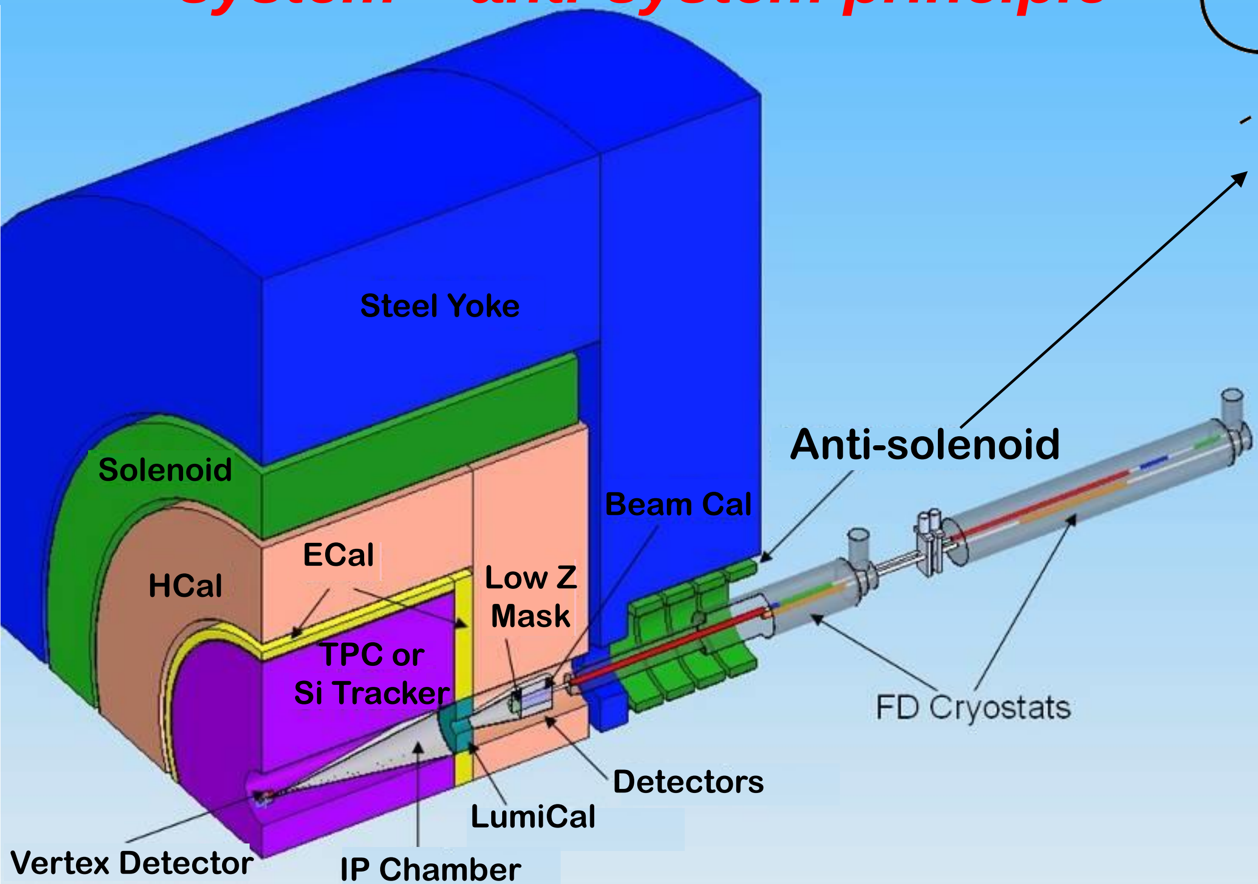
ILC Interaction Region…

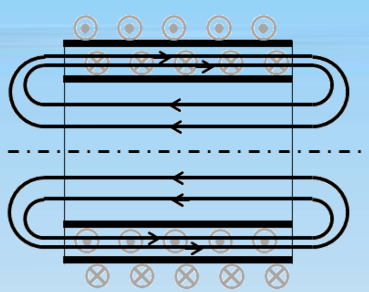
Dual anti-solenoid is used, to cancel its external field – this makes it force-neutral

Combination of nested doll & system – anti-system principle

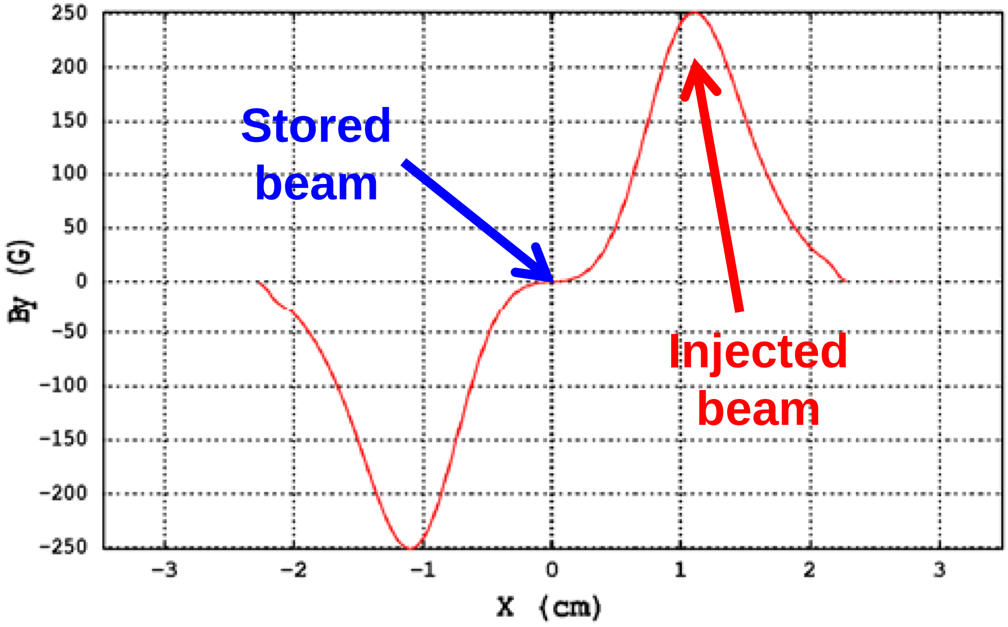


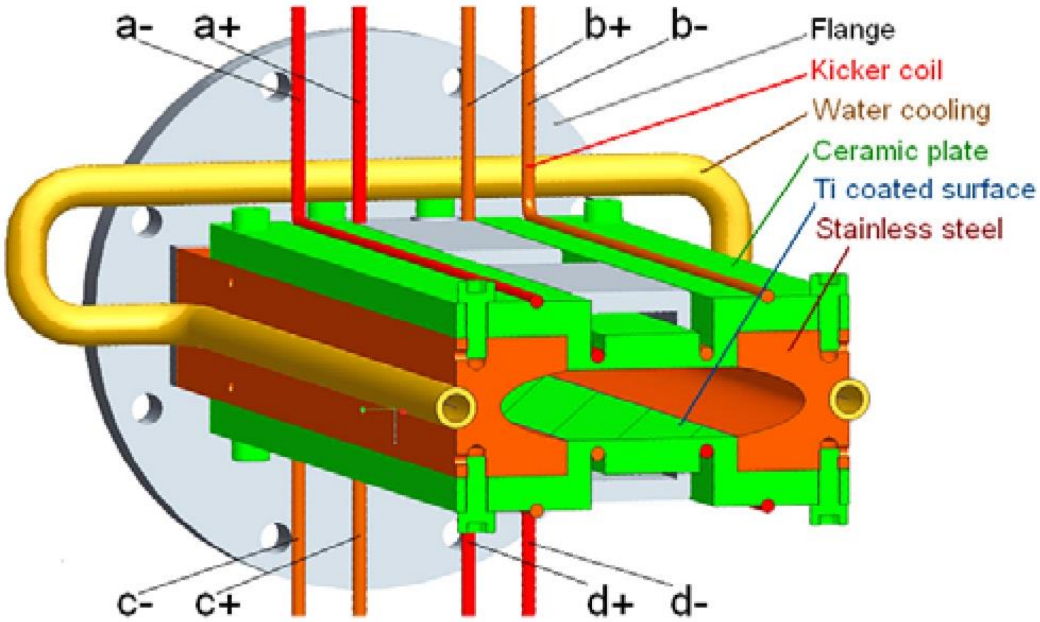
$I_2 = -I_1 * (R_1/R_2)^2$





Re-inventing injection to SR sources





Non-linear kicker:

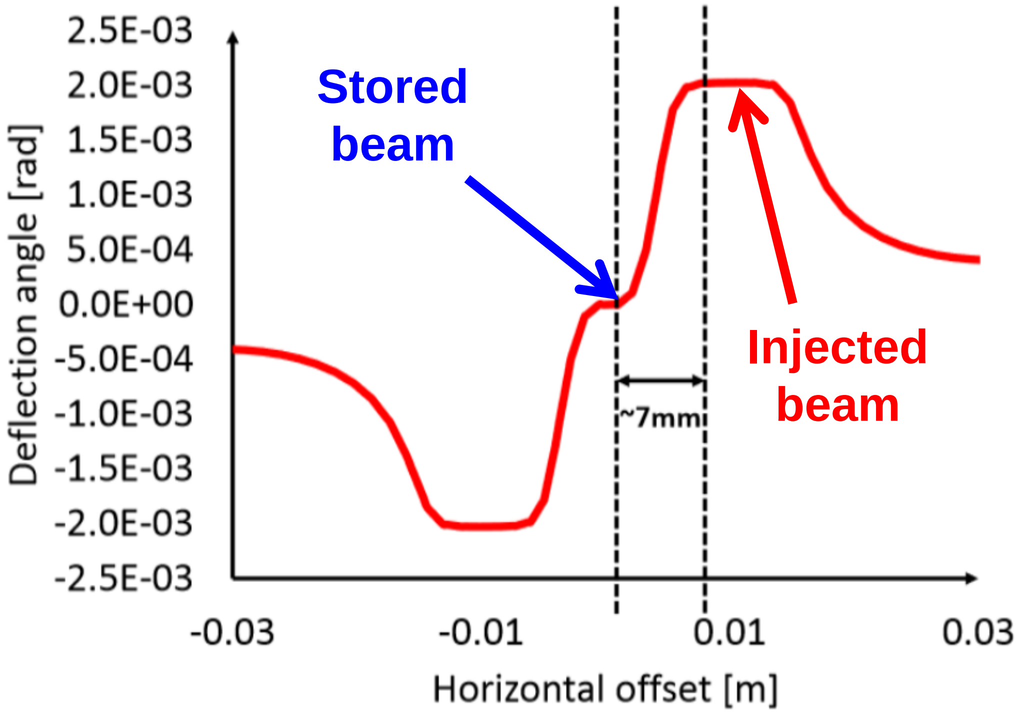
- Inner and outer wires create 0-field region
- Circulating beam see zero field
- Injected beam see max field

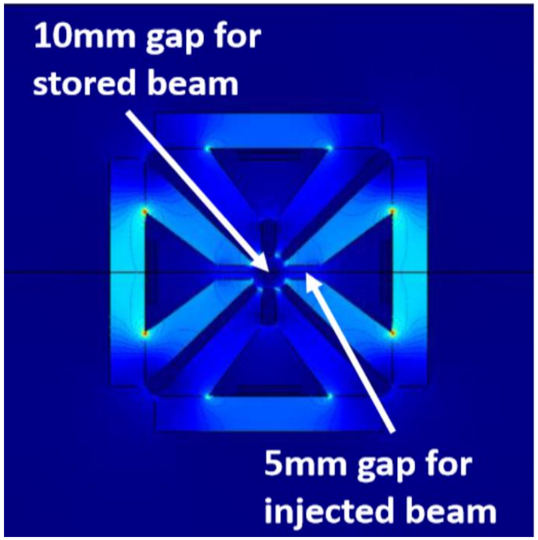
- Stronger focusing optics is possible

Combination of nested doll & system – anti-system principle

Atkinson, IPAC2011, BESSY II
https://accelconf.web.cern.ch/IPAC2011/papers/thpo024.pdf

Re-inventing injection to SR sources





Non-linear kicker:

- Octupole ferrite core kicker
- Circulating beam see zero field
- Injected beam see max field

- Stronger focusing optics is possible

Combination of nested doll & system – anti-system principle

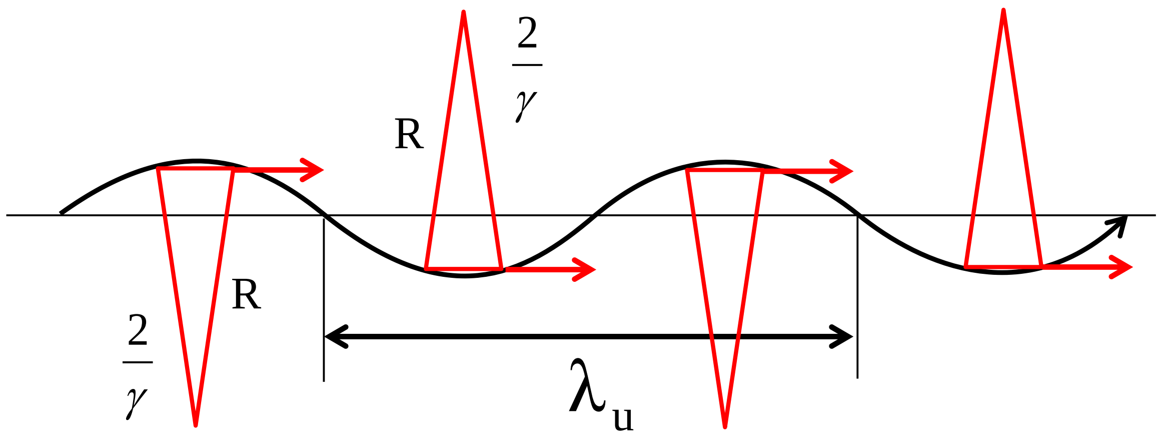
S White, IPAC2019, ESRF-EBS
https://accelconf.web.cern.ch/ipac2019/papers/mopgw008.pdf

Let’s now discuss Free Electron Lasers

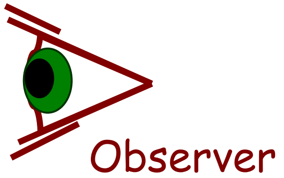
- **FEL overview**
- **FEL history**
  - **Why called laser?**
  - **Is it quantum device?**
  - **Connection to klystron and TWT**
  - **FEL invention path lessons**

Radiation from sequence of bends

Assume that bends are arranged in sequence with +-+-+- polarity with period λ_u, so that trajectory wiggles:



Observer will see photons emitted during travel along the arc $2R/\gamma$



If $2R/\gamma \ll \lambda_u/2$, then radiation emitted at each wiggle is independent

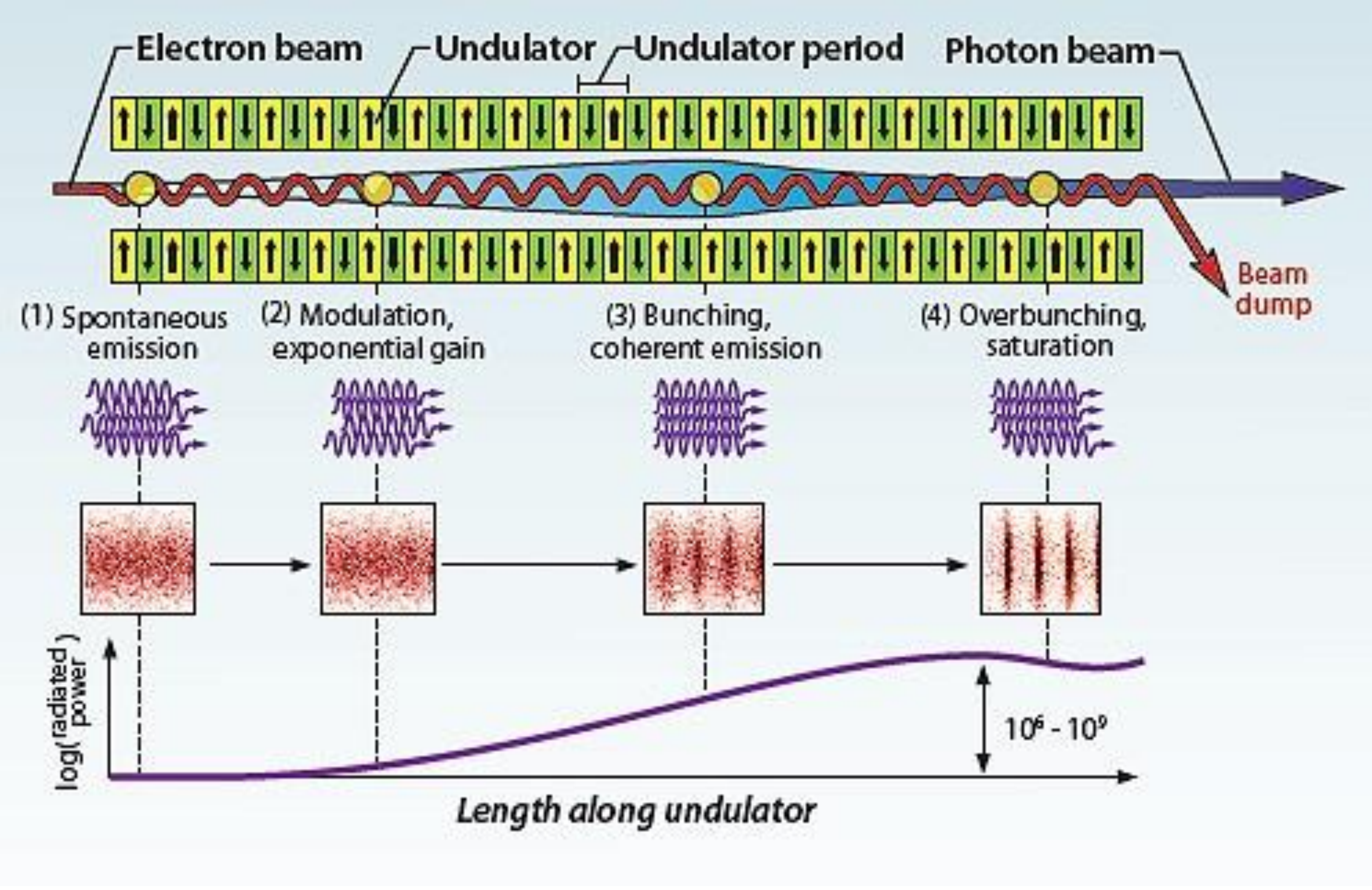
If $2R/\gamma \gg \lambda_u/2$ => regime where entire wiggling trajectory contribute to radiation

Define $K \sim \gamma\, \lambda_u/R$

$K \gg 1$ – wiggler regime

$K \ll 1$ – undulator regime

4th generation light source – Free Electron Laser Overview

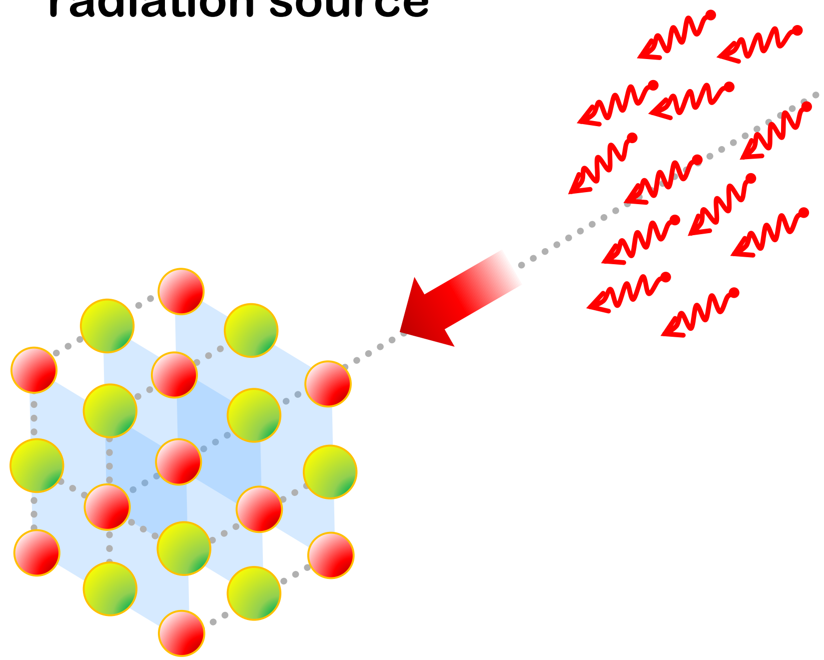


FEL basic concepts

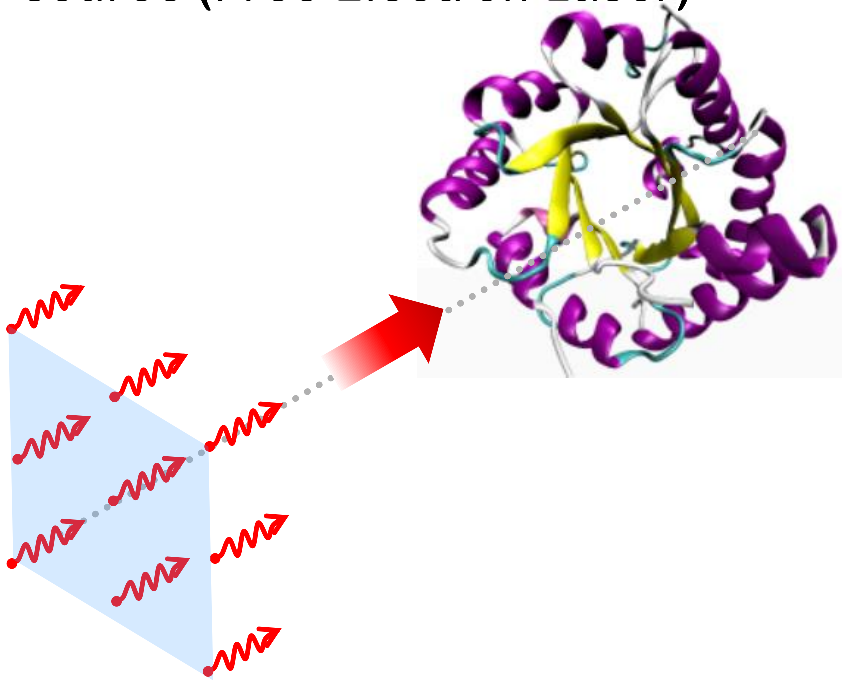
- In a storage ring the phase relationship between the radiation emitted by each electron is random and the spatial and temporal coherence of the radiation is limited
- The electrons emit radiation in an undulator incoherently
- In a FEL the electron interact back with the radiation emitted in the undulator
- Under certain conditions this process can generate a microbunching of the beam
- Microbunching happens mostly at the undulator resonant wavelength
- The electrons will now emit in phase with each other, coherently
- The radiation power (and brilliance) will scale as N_e^2 not as N_e

Incoherent SR => coherent

Incoherent synchrotron radiation source



Coherent synchrotron radiation source (Free Electron Laser)

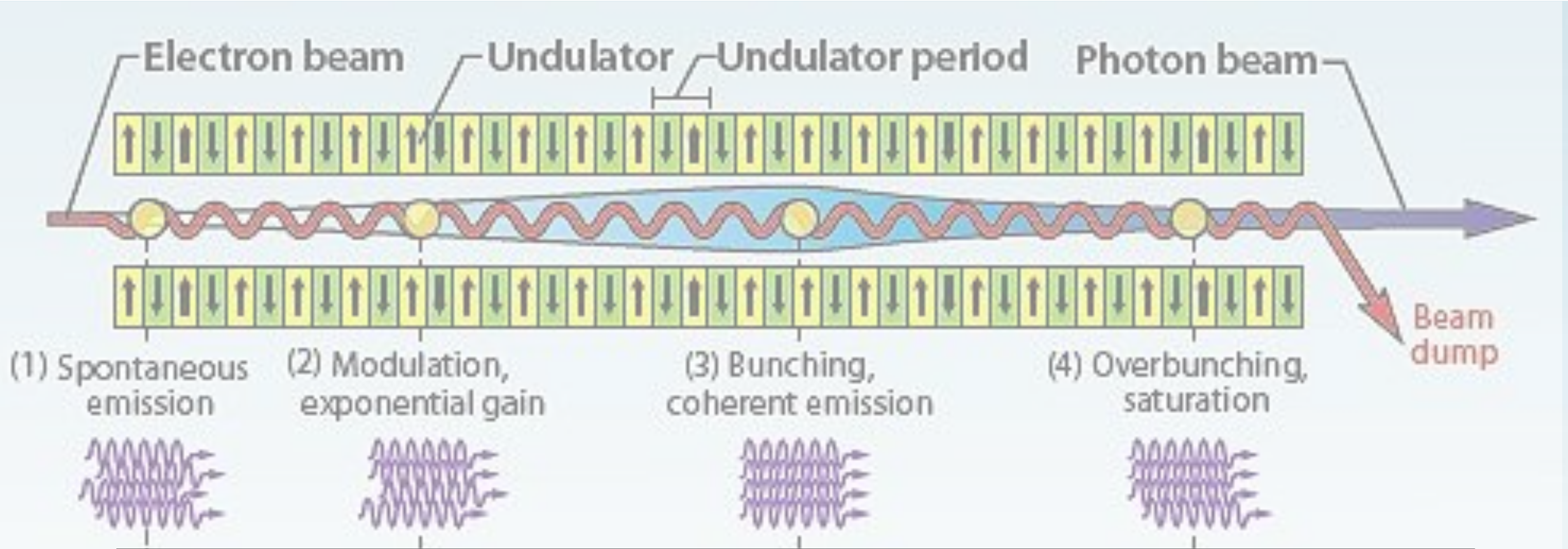


Era of studies of crystal structures by incoherent sources of X-rays

Era of studies of non-crystalline structures by coherent sources of X-rays

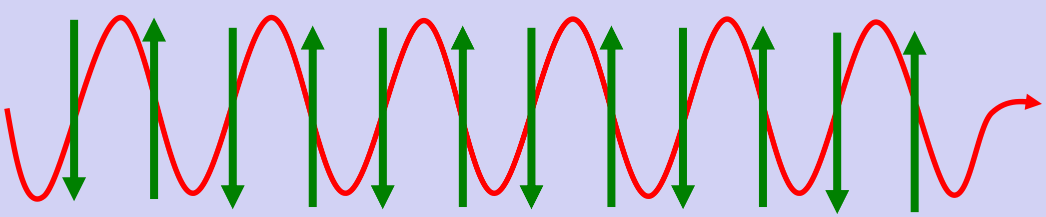
…and also this is an inventive principle “the other way around”

FEL beam-EM wave energy exchange - conceptually



Mechanism of beam – EM wave (light) energy exchange (conceptually):

Undulator creates wiggling beam trajectory

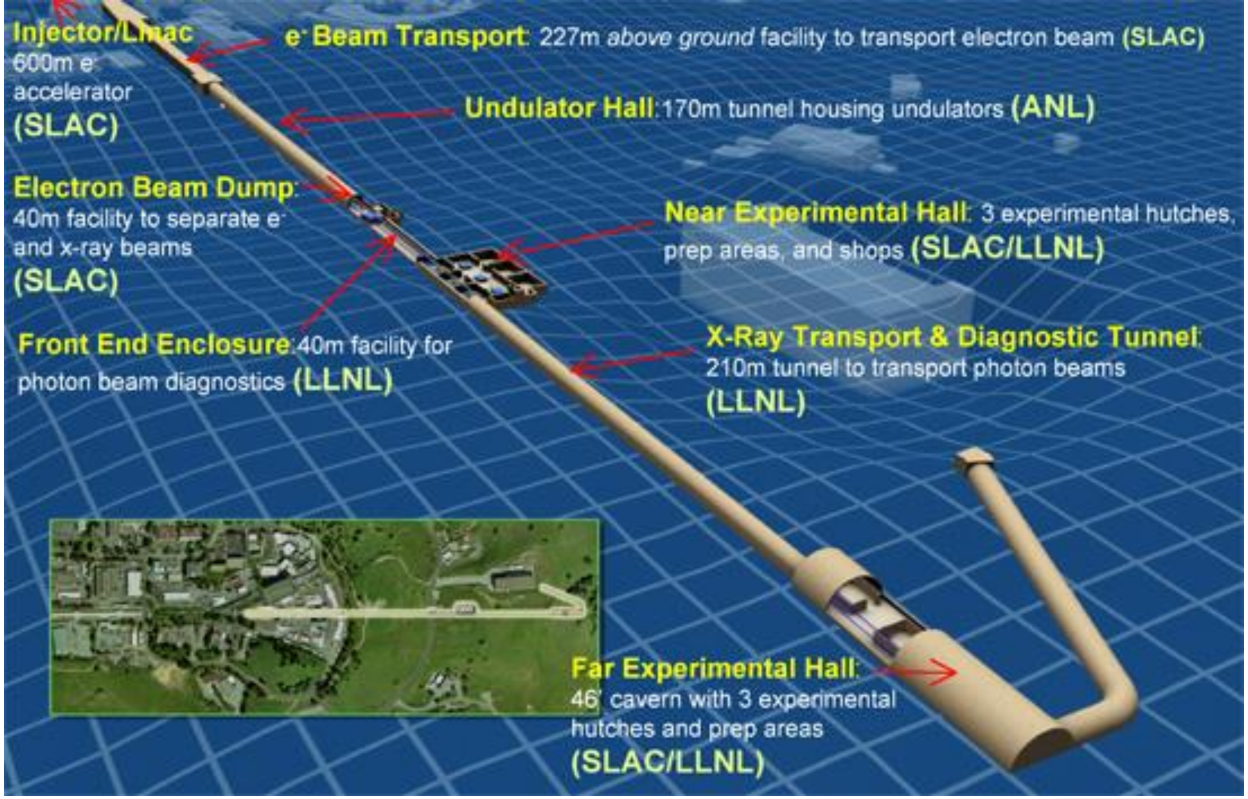


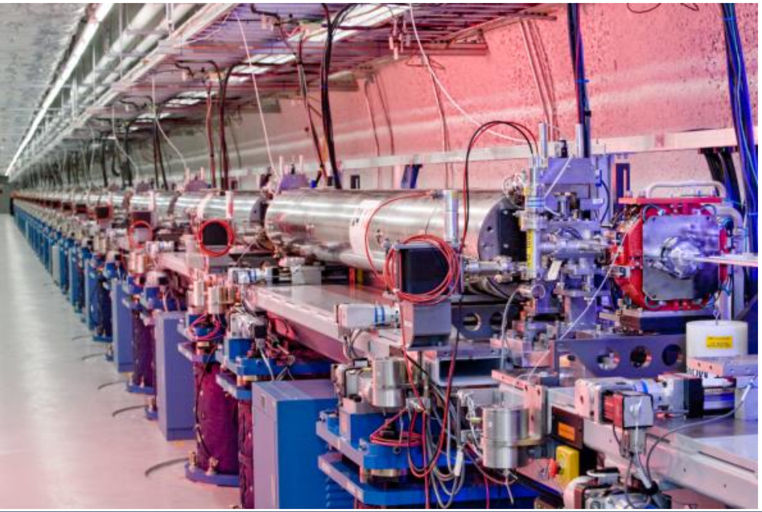
Transverse electric field of synchronous EM wave (light) is directed against particle transverse velocity → energy removed from the particles and thus fed into the EM wave

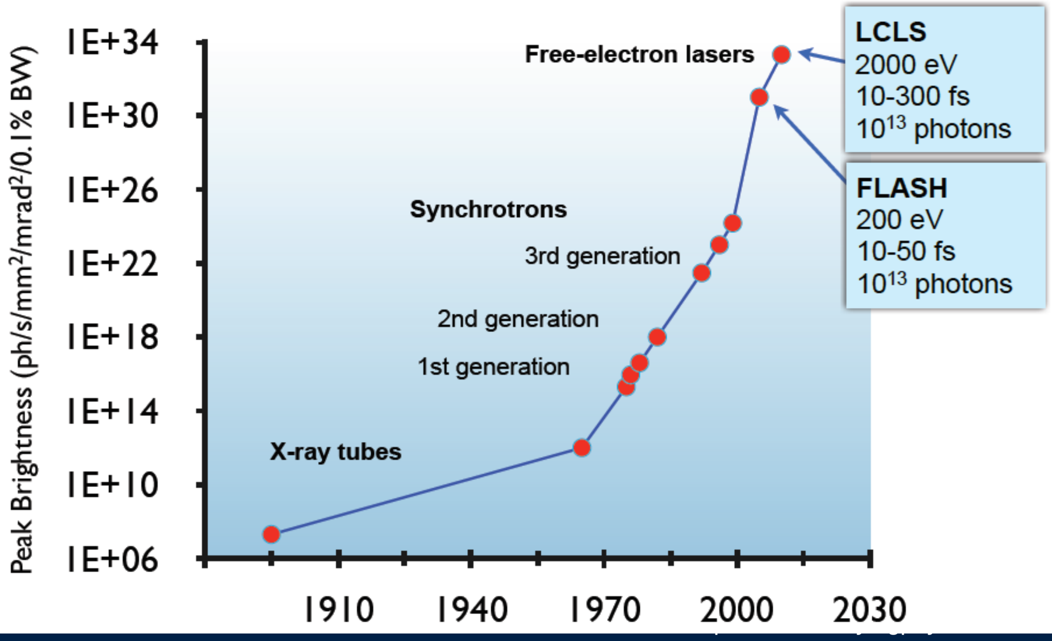
4th generation light source – example

X-ray FEL-

LCLS at SLAC







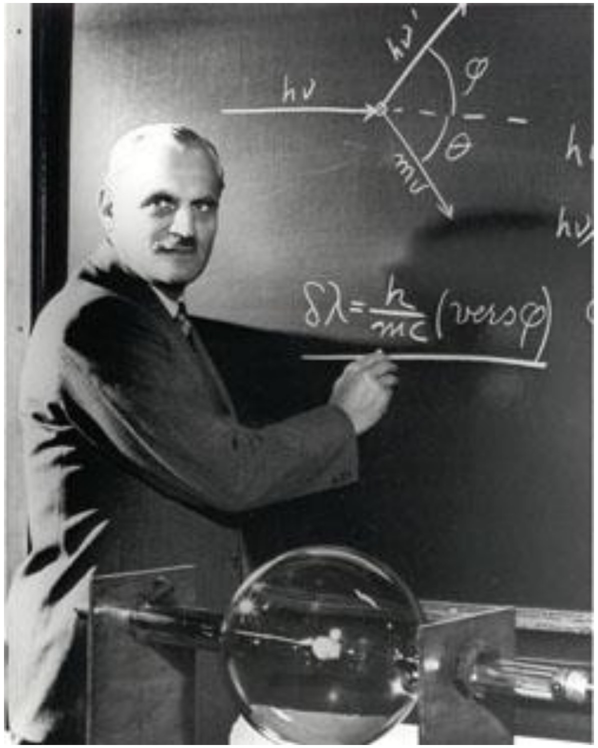
Path to FEL invention

- – Thomson and Compton scattering ~1920
- – Klystron – 1937
- – Travelling Wave Tube – 1947 - 1950
- – Undulator – 1947- 1950
- – Ubitron – 1957
- – Laser – 1958
- – FEL – 1970

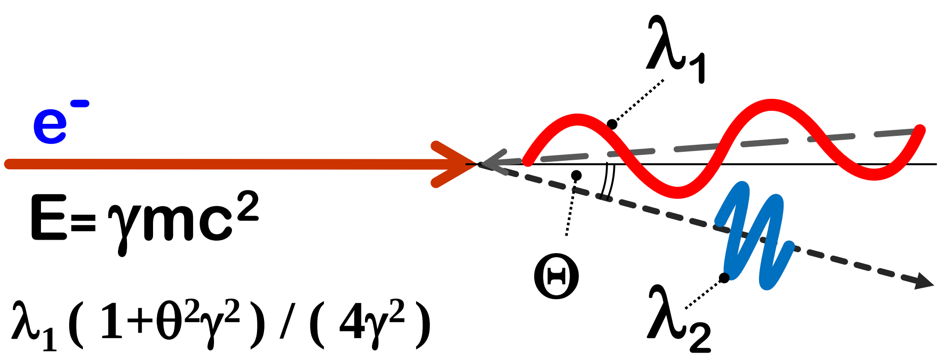
Historical connections inspired by Richard Walker’s lecture on FELs, 2002
https://indico.cern.ch/event/412220/

Compton scattering

In collision between a high E free electron and a low energy photon a substantial fraction of the electron energy can be transferred to the photon As a result, in the observer frame, the photon is backscattered with a significant energy boost .
This process is known as Compton backscattering



Inverse Compton scattering:
photon gains energy after interaction



$$\lambda_2 = \lambda_1 \,(\, 1+\theta^2\gamma^2 \,) \,/\, (\, 4\gamma^2 \,)$$

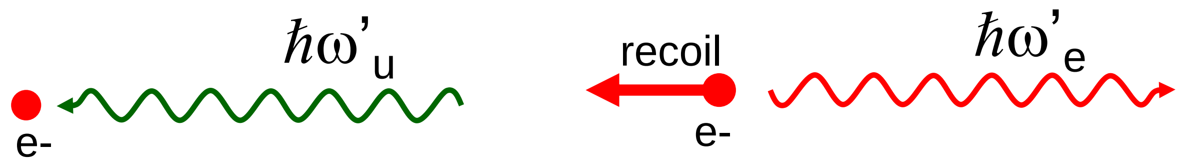
- **Examples for λ_1= 532 nm (2.33 eV)**
  - e- 5.11 MeV (γ =10), λ_2= 1.33 nm (0.93 keV)
  - e- 18.6 MeV (γ =36.5), λ_2= 0.1 nm (12.4 keV)

First Description of FEL

Undulator magnetic field is seen by relativistic electron as an EM wave

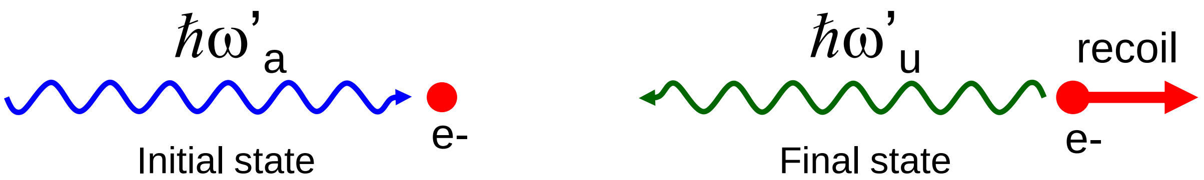
The electrons can either scatter an undulator "photon" in the forward direction and loose momentum (Emission) :

Emission:



Or scatter a laser photon in the backward direction and gain momentum (Absorption):

Absorption:



JOURNAL OF APPLIED PHYSICS VOLUME 42, NUMBER 5 APRIL 1971

Stimulated Emission of Bremsstrahlung in a Periodic Magnetic Field

JOHN M. J. MADEY

Physics Department, Stanford University, Stanford, California 94305

(Received 20 February 1970; in final form 21 August 1970)

The Weizsäcker–Williams method is used to calculate the gain due to the induced emission of radiation into a single electromagnetic mode parallel to the motion of a relativistic electron through a periodic transverse dc magnetic field. Finite gain is available from the far-infrared through the visible region raising the possibility of continuously tunable amplifiers and oscillators at these frequencies with the further possibility of partially coherent radiation sources in the ultraviolet and x-ray regions to beyond 10 keV. Several numerical examples are considered.

A closer resemblance is to be found between this paper and that of Pantell, Soncini, and Puthoff[7] who proposed the use of stimulated inverse Compton scattering but were restricted in gain to the infrared by

FEL and Lasers. Is FEL a "Laser"?

The first analysis of the FEL (Madey, 1971) was made using quantum theory, and the physical principles of FEL operation were considered different to those of earlier devices…

J.M.J. Madey, J. Appl. Phys., 42 (1971):

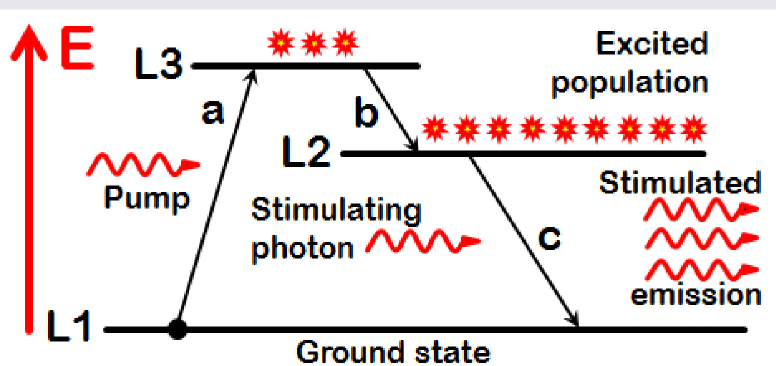
The gain available due to stimulated emission is proportional to the spontaneous transition rate into a definite, if unspecified final photon state (typically, one of the resonant modes of an optical cavity), taking into account all possible combinations of initial photon and electron momenta leading to that state. The quantity required is

Γ_d = spontaneous transition rate into a definite final photon state

$$= (2\pi/\hbar)|\langle f | H' | i \rangle|^2 \rho_i, \tag{10}$$

where ρ_i is the appropriate density of initial states. The

Three level laser



Invented 1958

a. **The pump gets population from ground state L1 to the higher energy level L3**
b. **The excited population gets from L3 to L2 through non radiative decay**
   - **The lifetime of L3 is very short and all the population in state L3 decays to state L2**
c. **Stimulated emission from L2 to state L1**
   - **Lifetime of energy state L2 is long => population inversion occurs with respect to state L1**
   - **Once the population inversion is obtained, stimulated emission will give optical gain**

FEL and Lasers. Is FEL a “Laser”?

- The first analysis of the FEL (Madey, 1971) was made using quantum theory, and the physical principles of FEL operation were considered different to those of earlier devices
- It was noted however that the Planck constant $\hbar$ cancelled out of the final equations and many doubts were expressed whether it was a 'true' laser ...

- Later, a fully classical picture was developed* (Hopf et al., Colson, 1976):

"the quantum theory of a free-electron laser is extremely tedious, and is neither desirable nor necessary" Hopf et al., 1976

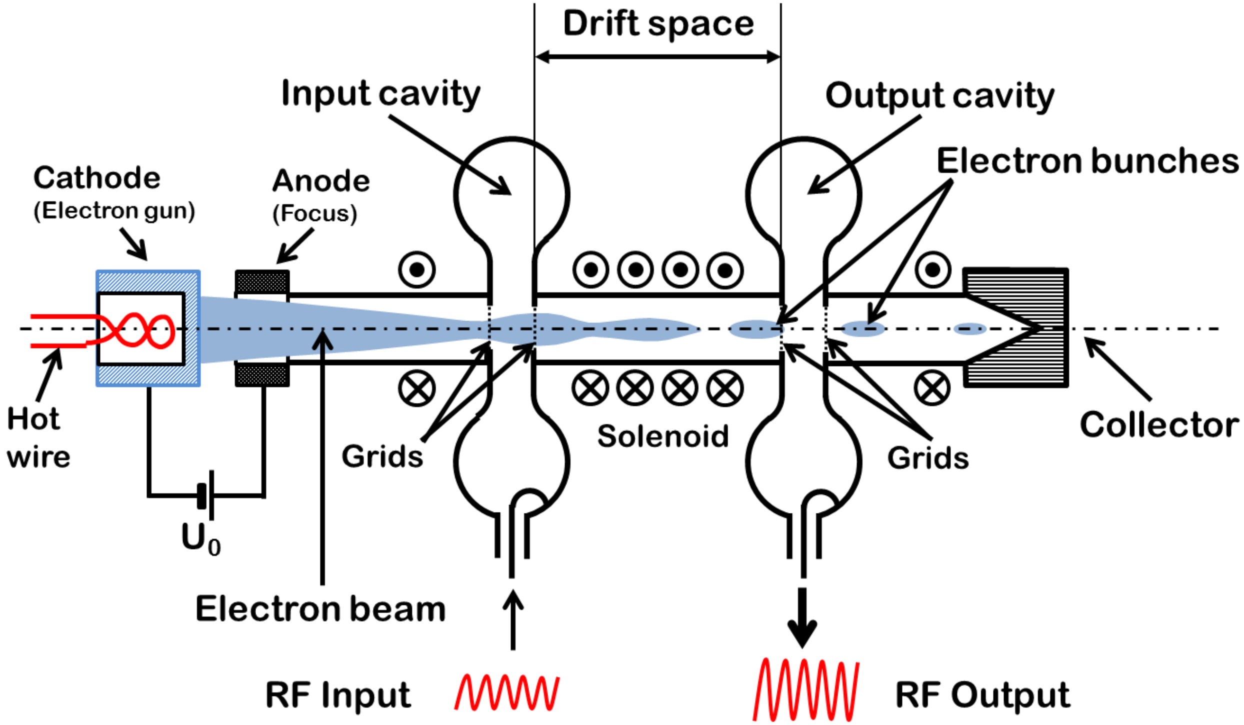
- The physical picture is of electrons bunching on the scale of the radiation wavelength and therefore emitting radiation coherently
- Slightly later a connection was made with earlier theoretical work showing that the FEL did indeed operate according to the same principles as earlier devices (Kroll et al., 1978) and so it eventually became clear that the FEL was essentially the latest in a long series of electron beam devices that generate coherent radiation

* and also separately in R.B. Palmer, J. Appl. Phys. 43 (1972) 3014

Klystron

Sigurd and Russell Varian, who were working on IOT in 1937, added a second cavity resonator for signal input to the inductive output tube

This input resonator acted as a pair of inductive grids to alternately "bunch" and release packets of electrons down the drift space of the tube, so the electron beam would be composed of electrons traveling at different velocities

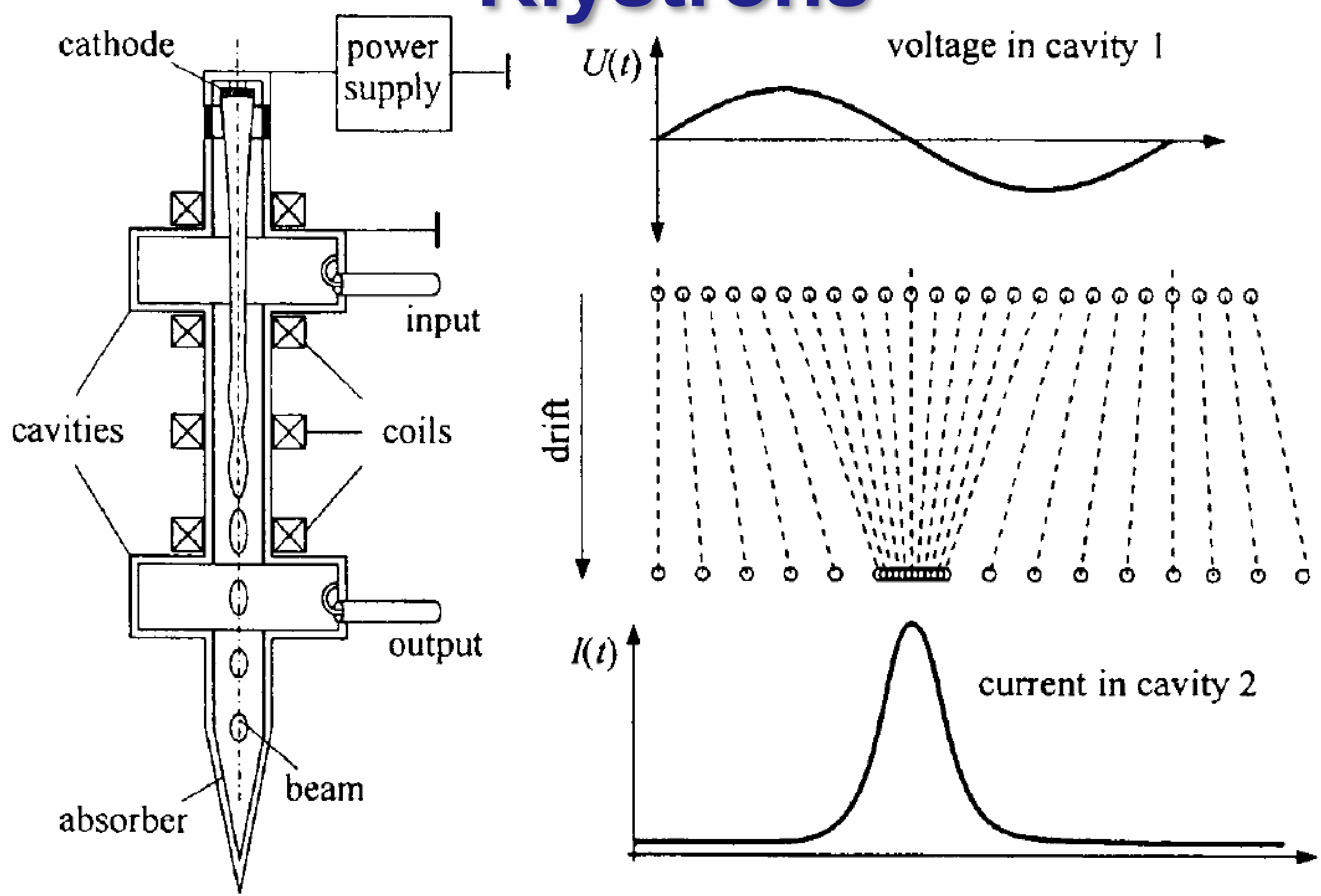


Bunched beam – coherent radiation

This "velocity modulation" of the beam translated into the same sort of amplitude variation at the output resonator, where energy was extracted from the beam

The Varian brothers called their invention a *klystron*

Klystrons



This "velocity modulation" of the beam translated into the same sort of amplitude variation at the output resonator, where energy was extracted from the beam

Travelling Wave Tube

(Kompfner, 1947; Pierce, 1950)

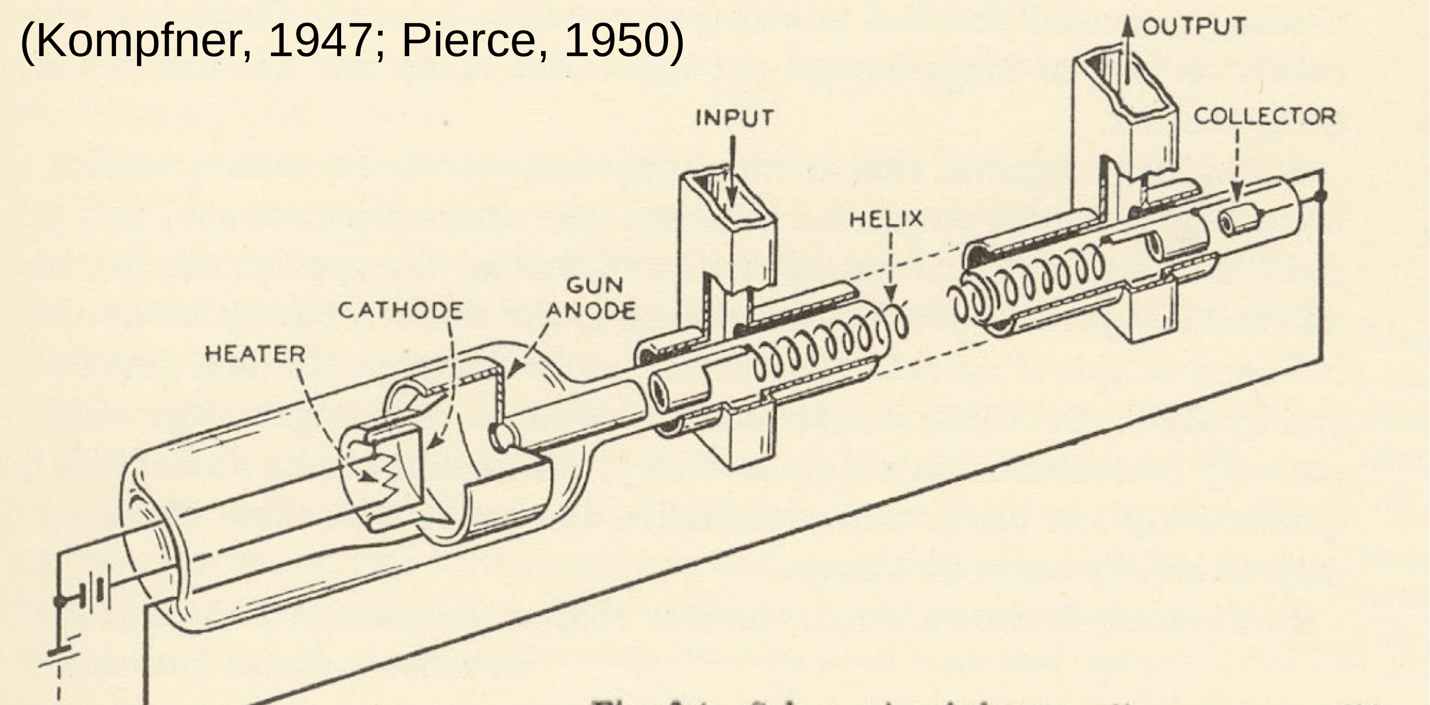
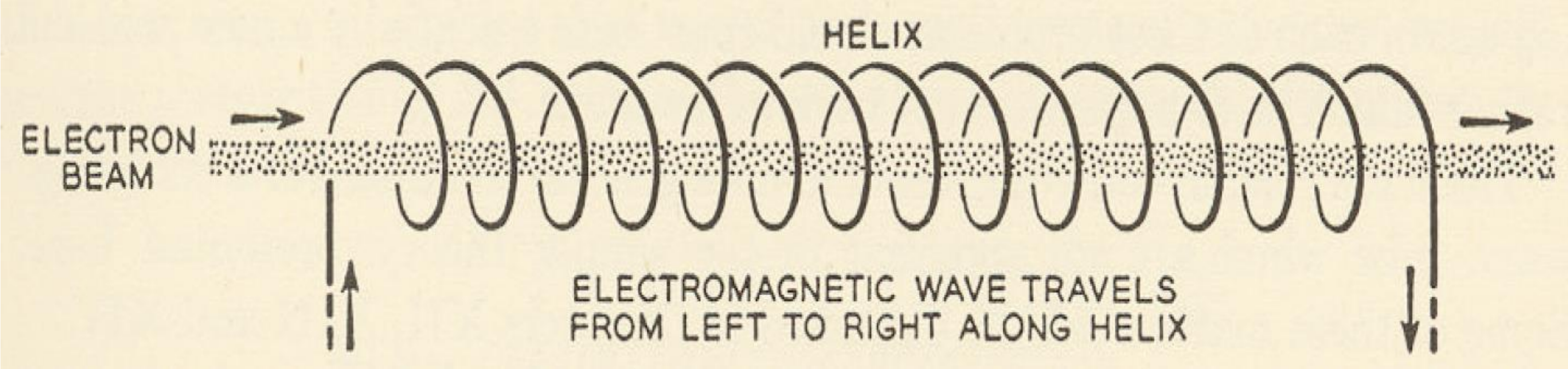
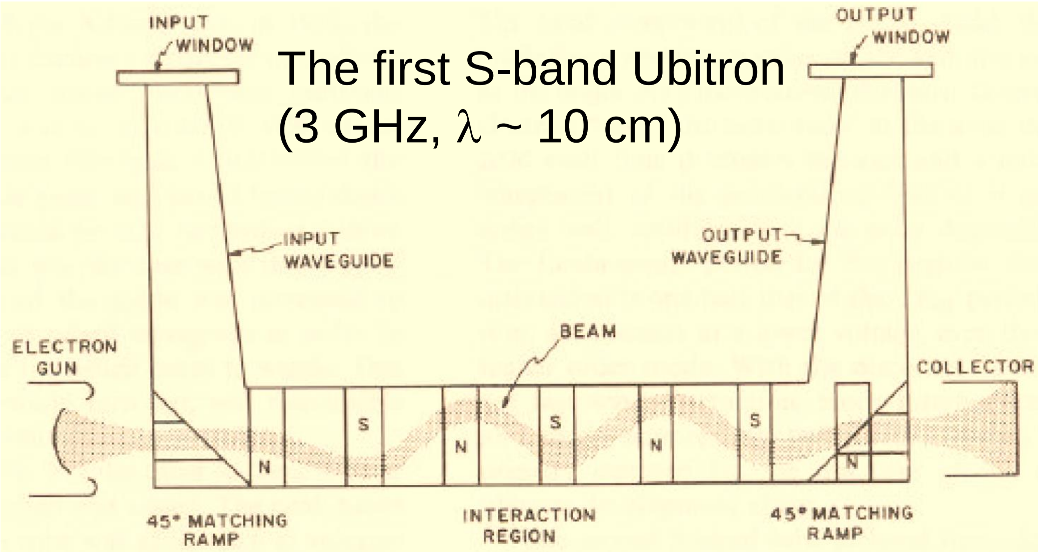


Fig. 2.1—Schematic of the traveling-wave amplifier.

Helix slows down the EM wave allowing synchronism with the electron beam



The UBITRON



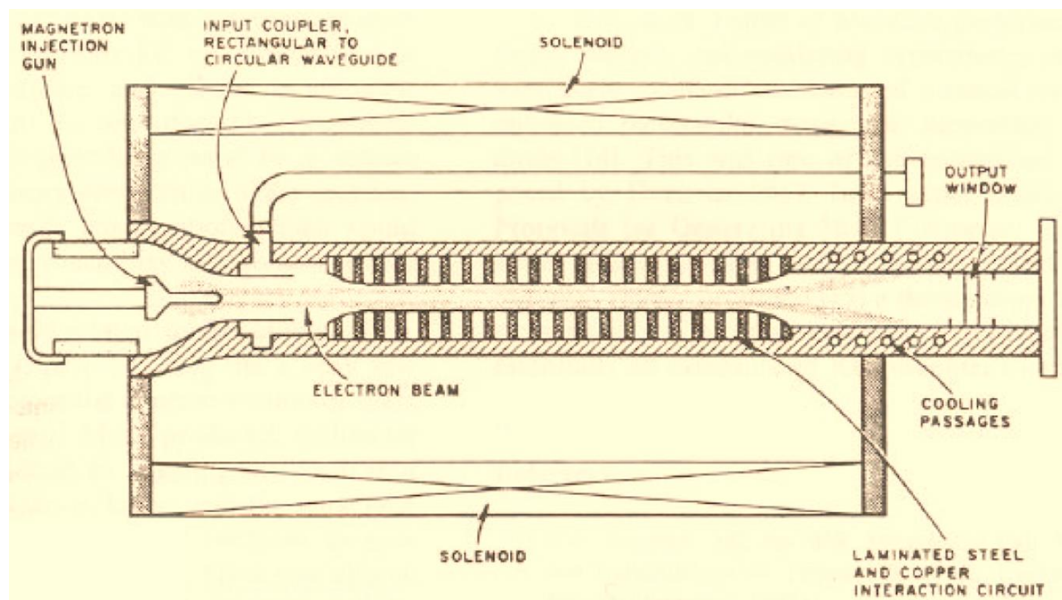
The first S-band Ubitron
(3 GHz, λ ~ 10 cm)

Undulating Beam InTeRactiON
Invented in 1957 (R.M. Phillips)

- A "fast wave" structure with a new interaction mechanism - undulation of the electron beam
- Both a microwave tube and a non-relativistic FEL amplifier

R. M. Phillips, *IRE Trans. on Electron Devices*, vol. 7, no. 4, pp. 231-241, Oct. 1960

V-band Ubitron,
54 GHz, λ ~ 5 mm
70 kV beam energy
150 kW output power
(hollow beam)



R.M. Phillips, Nucl. Instr. Meth. A272 (1988) 1.

The Ubitron invention

The ubitron (acronym for undulating beam interaction) is an FEL which was setting records for rf power generation 15 years before the term "free electron laser" was coined. As is so often the case, the invention of the ubitron was accidental. The year was 1957 and I was searching, at the GE Microwave Lab, for an interaction which would explain why an X-band periodically focussed coupled cavity TWT oscillated when a solenoid focused version did not. The most apparent difference between the two was the behavior of the electron beam; one wiggled while the other simply spiraled. Out of a paper study of ways of coupling an rf wave to an undulating axially symmetric electron beam came the idea of coupling to the TE_{01} mode by allowing the wave to slip through the beam such that the electric field would reverse direction at the same instant the electron velocity reversed.

From R.M. Phillips, Nucl. Instr. Meth. A272 (1988):

To remind – the TE01 mode has transverse electric field oscillating along the waveguide

The Ubitron invention

From R.M. Phillips, Nucl. Instr. Meth. A272 (1988):

The potential for generating super power with the new fast wave amplification was immediately obvious. Here was a beam–wave interaction which required no slow wave circuit, and the coupling region could be very large. Any of the waveguide and beam configurations illustrated in fig. 1 would provide 100 times the cross sectional area of a conventional slow wave TWT. Furthermore, the preferred rf mode, TE_{01}, was unique in having no axial wall currents, so mode selection should be straightforward, even in an overmoded waveguide. Because propagation was fast wave, maximum rf field was well removed from the guide walls.

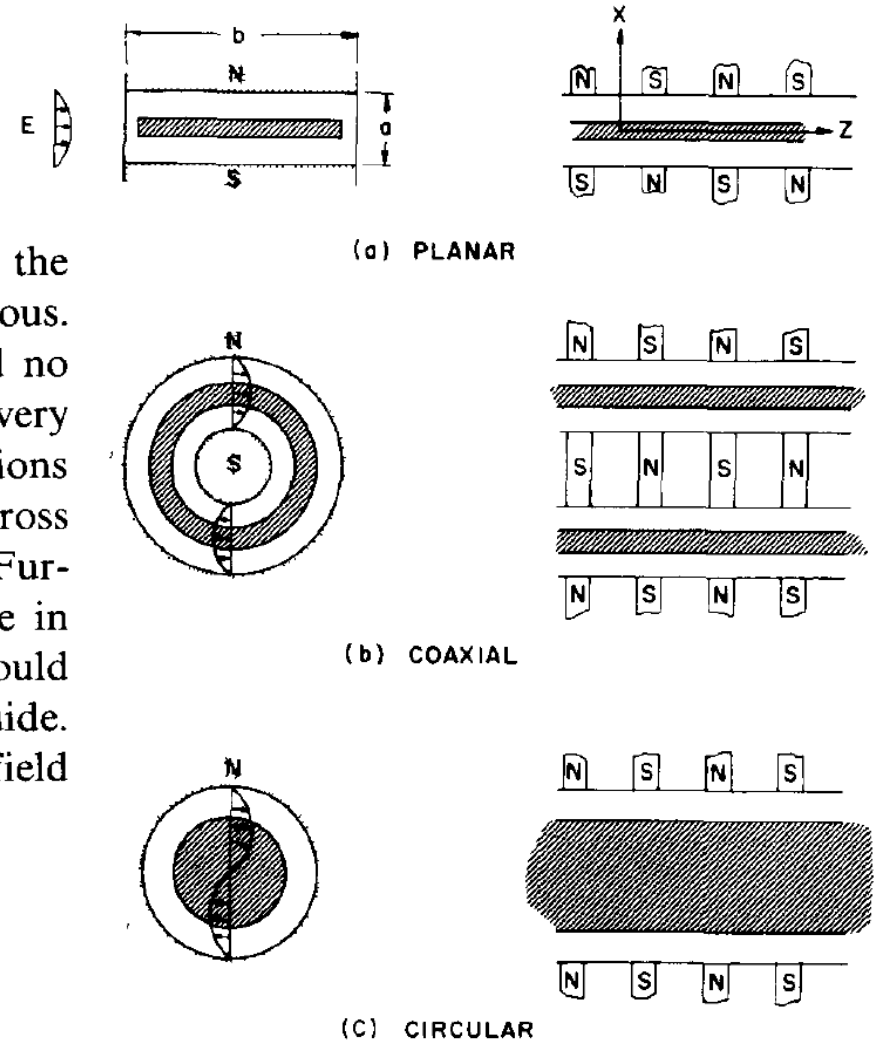


Fig. 1. Examples of beam-guide ubitron configurations which provide 100 times the interaction area of a TWT.

The Ubitron invention

R.M. Phillips calculated (on an analog computer!) EM-wave – wiggling beam interaction and saw bunching the beam:

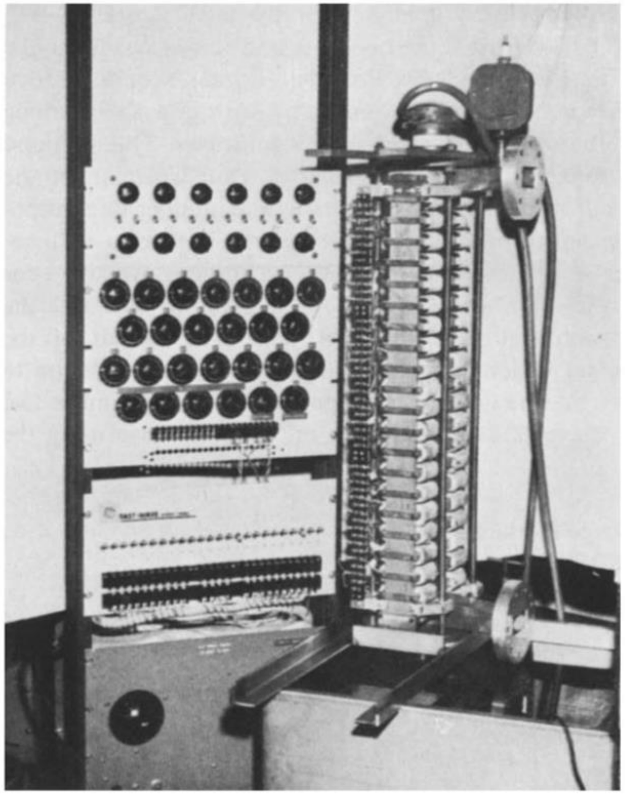


Fig. 5. Photograph of S-band ubitron which produced 1.2 MW of power. Coil currents were rheostat controlled. Cathode is hidden in the oil tank.

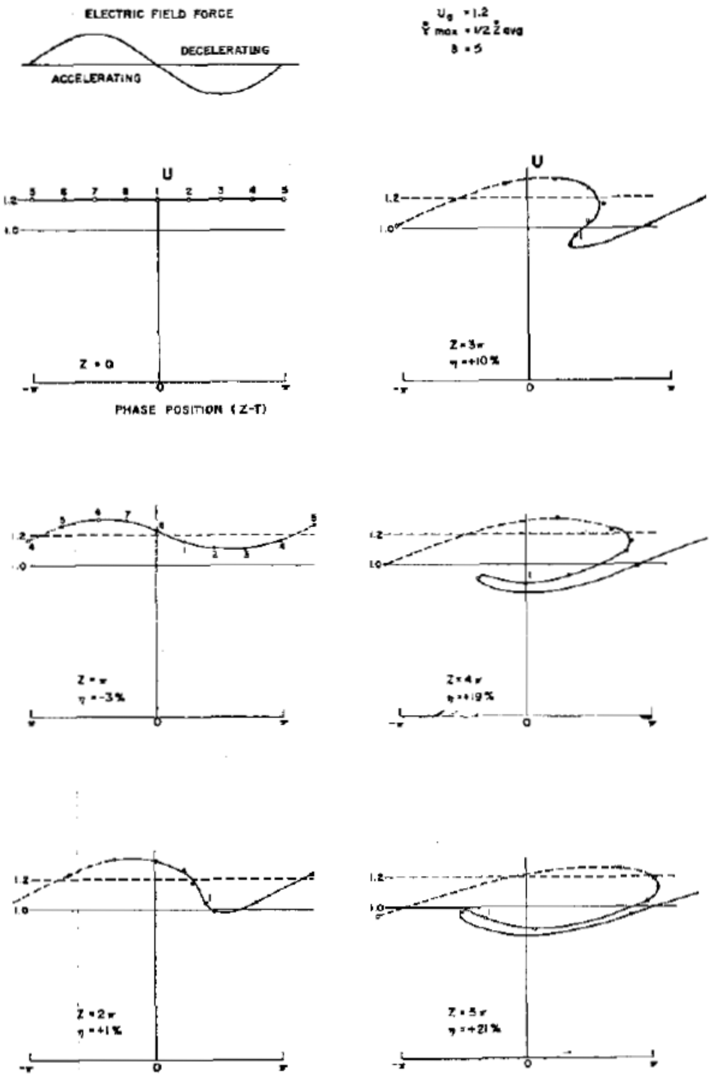
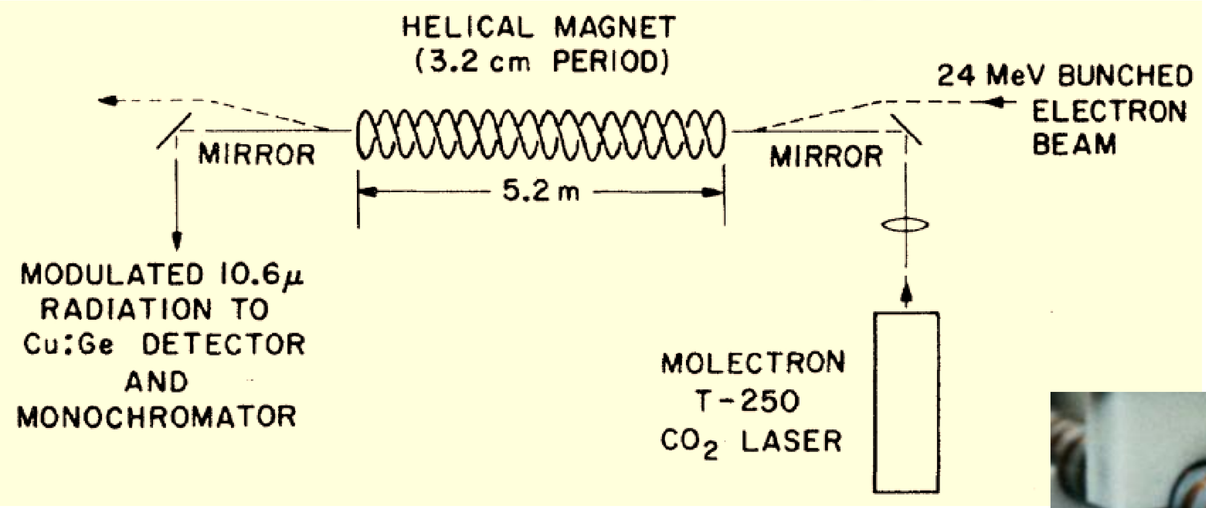


Fig. 4—Phase-space diagrams for electrons in a constant amplitude wave measured at intervals of $1/2\ P$ in z (π in Z).

From R.M. Phillips, Nucl. Instr. Meth. A272 (1988):

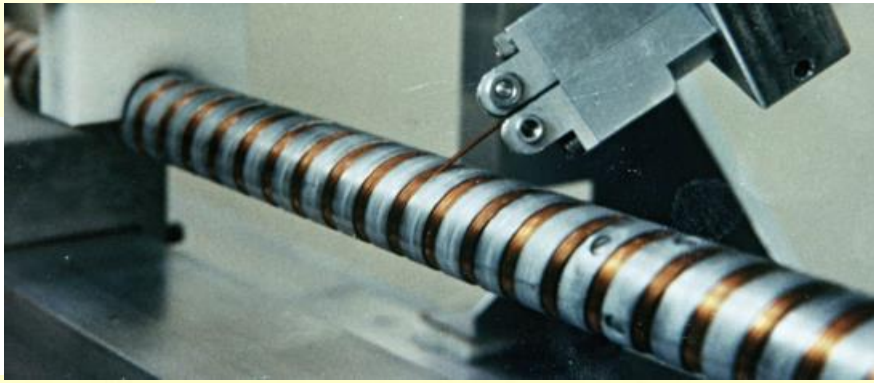
First FEL experiments at Stanford



The First FEL Amplifier

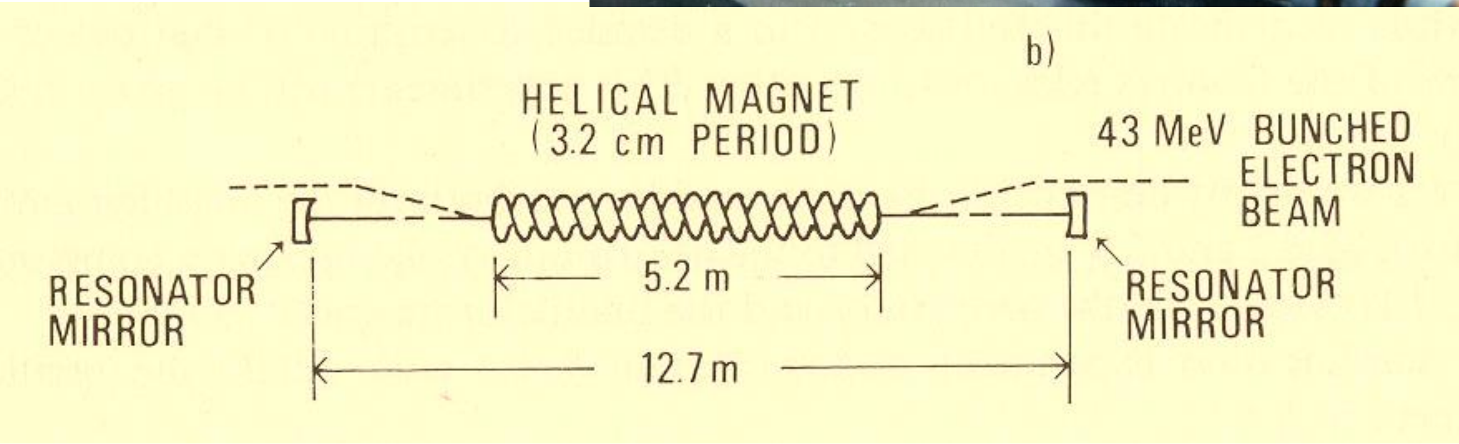
E = 24 MeV
I_{peak} = 70 mA
λ = 10.6 μm
Peak gain = 7 % per pass

L.R. Elias, W.M. Fairbank, J.M.J. Madey, H.A. Schwettman, and T.I. Smith, Phys. Rev. Lett. 36, 717, 1976



The First FEL Oscillator

E = 43 MeV
I_{peak} = 2.6 A
λ = 3.4 μm
<Power> = 0.36 W
Peak power = 7 kW



D. Deacon et al., Phys. Rev. Lett. 38 (1977) 892

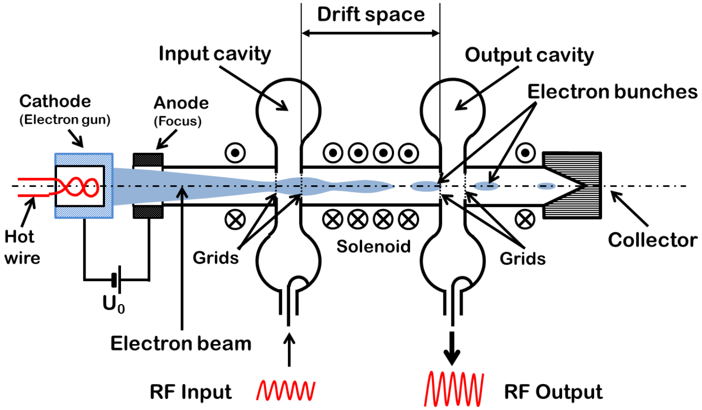
Path to FEL invention

- – **Thomson and Compton scattering ~1920**
- – **Klystron – 1937**
- – **Travelling Wave Tube – 1947 - 1950**
- – **Undulator – 1947- 1950**
- – **Ubitron – 1957-1960**
- – **Laser – 1958**
- – **FEL – 1970**

… a connection was made with earlier theoretical work showing that the FEL did indeed operate according to the same principles as earlier devices and so it eventually became clear that the FEL was essentially the latest in a long series of electron beam devices that generate coherent radiation…

This reminds us the connection between radar and CPA invention and the overall trend of going from microwave range into optical range

Path to FEL and inventive principles



Use principle "continuity of useful action": add continuous cavity to interact with beam – an EM wave

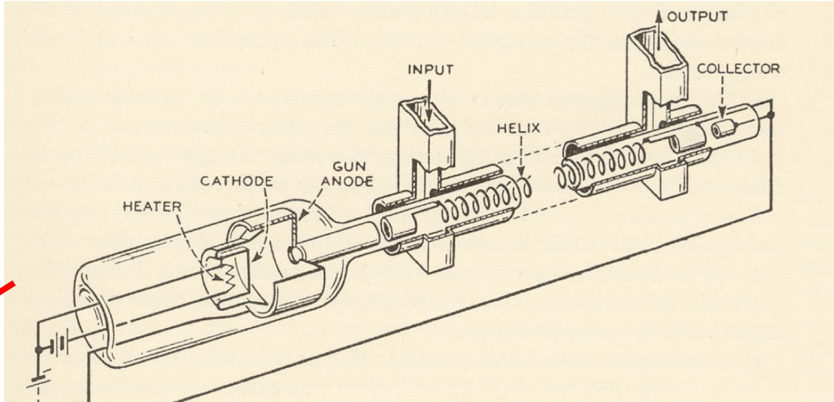
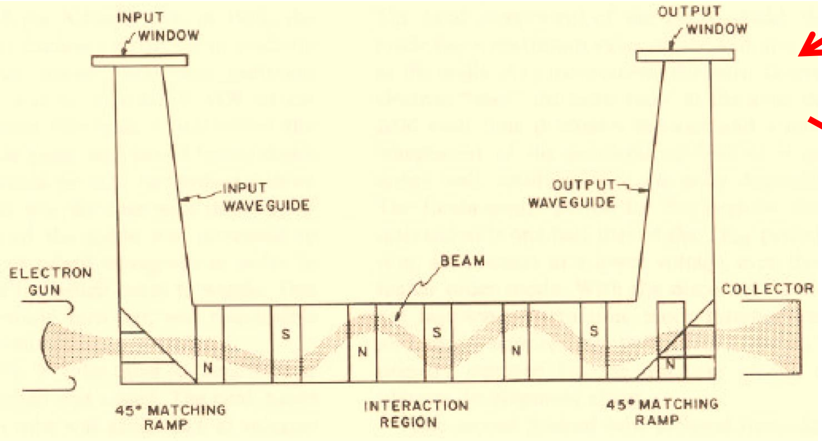
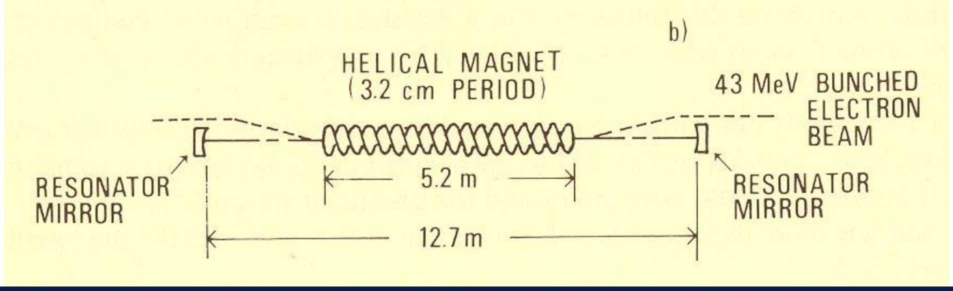


Fig. 2.1—Schematic of the traveling-wave amplifier.

Use principle "going to another direction": add wiggling motion that connects EM wave with the largest source of energy – longitudinal motion



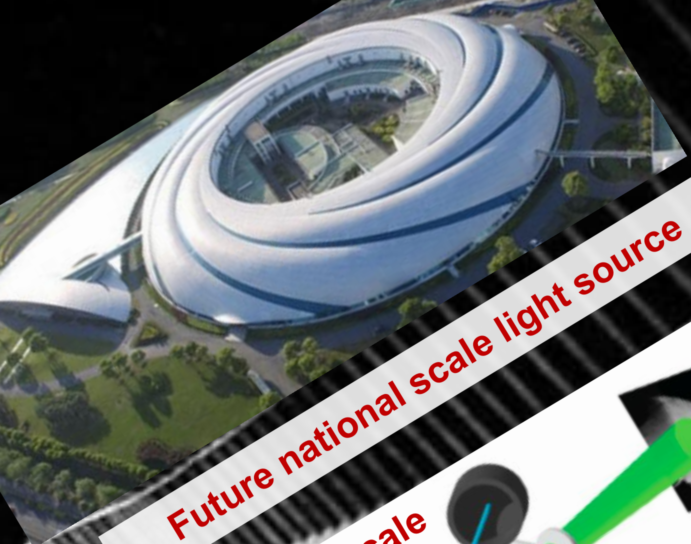
Use principle "from microwave to optical"
And arrive to FEL



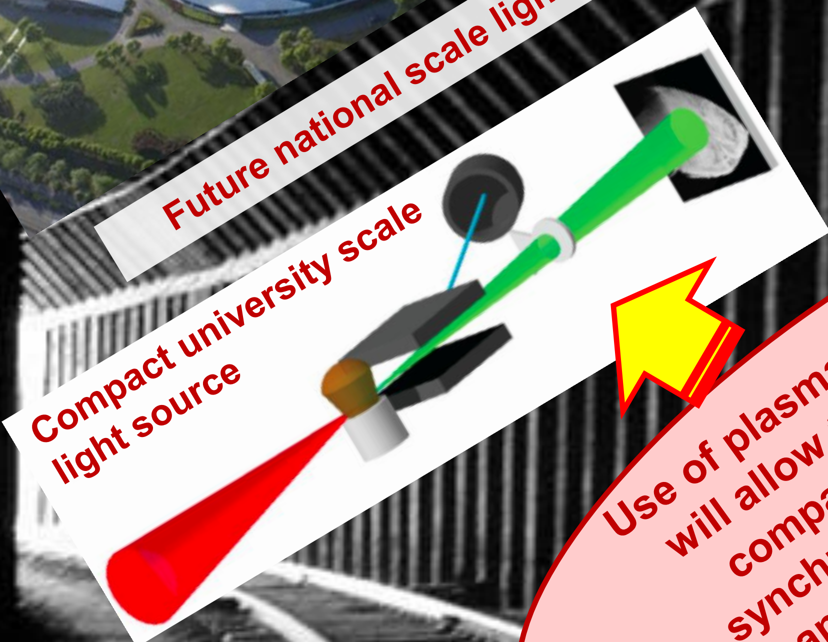
Evolution of computers and light sources

"IBM bringing out a personal computer would be like teaching an elephant to tap dance" cca. 1981

Evolution of computers and light sources



Future national scale light source



Compact university scale light source

Use of plasma acceleration will allow to create very compact sources of synchrotron radiation – change of the paradigm

Further evolution of light sources

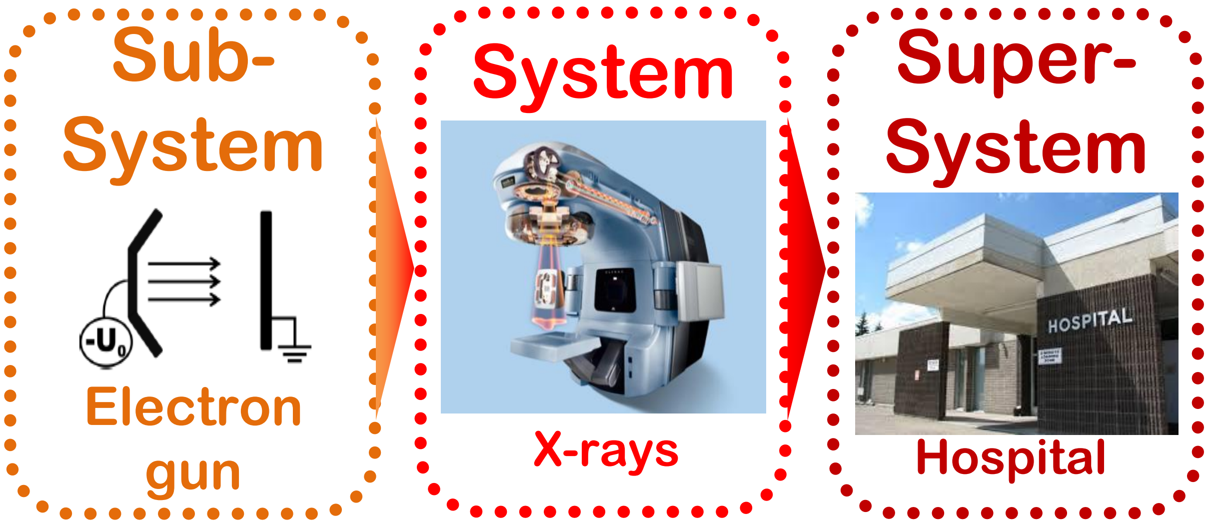
Let’s assume that laser-plasma FEL is working

What are long-terms perspectives and evolution of light sources then?

Let’s apply the TRIZ general laws of evolution

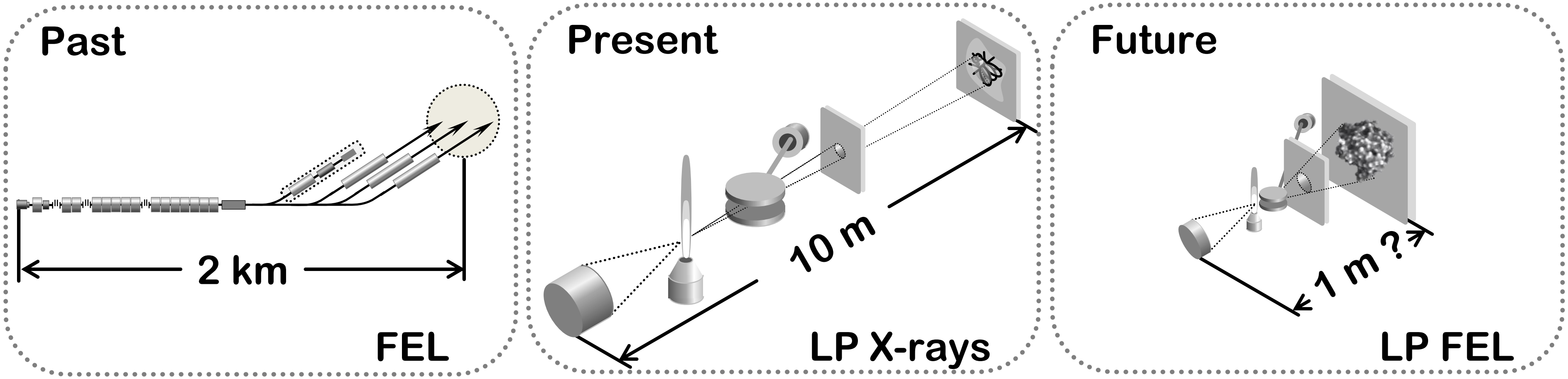
Transition to a super-system

- **Kinematic laws (standard TRIZ)**
  - The law of transition to a super-system



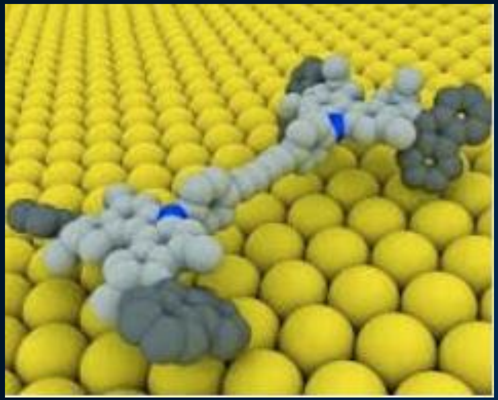
“a system exhausting possibilities of further significant improvement is included in a super-system as one of its parts”

FEL evolution forecast



FEL will be so compact and developed that it can become part of another system, and that system in turn part of super-system

Nobel prize 2016 – molecular machines



Pierre Sauvage, J. Fraser Stoddart, and Ben L. Feringa, Chemistry Nobel Prize 2016

TRIZ evolution laws allow to predict what parts of molecular machine would be invented next:

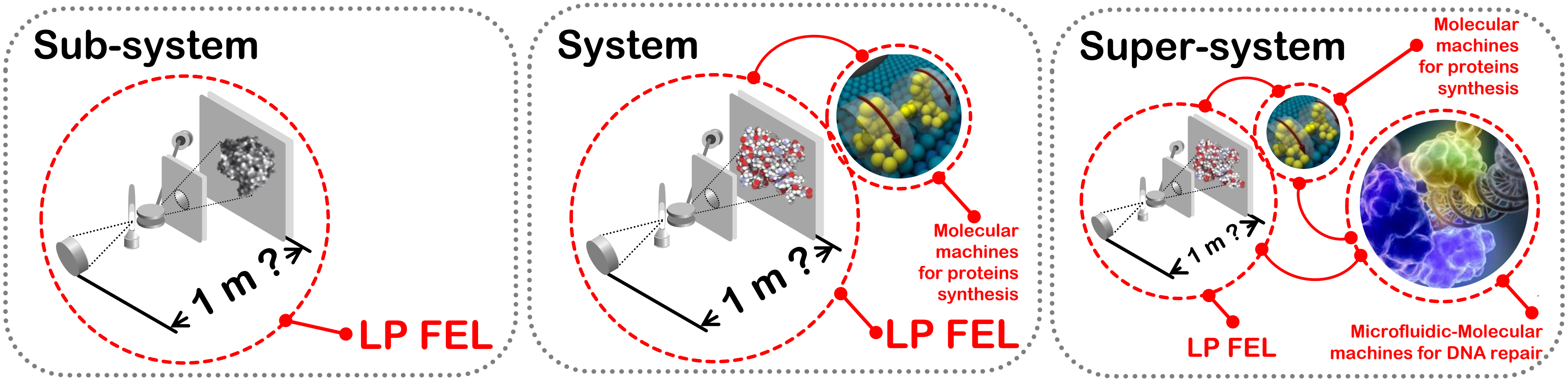
- Static Laws
  - The law of the completeness of the parts of the system
    - 4 parts: engine, transmission, working unit, control element
  - The law of energy conductivity of the system
    - every technical system is a transformer of energy and it should circulate freely and efficiently through its 4 main parts

Most importantly –
these machines can become part of another super-system

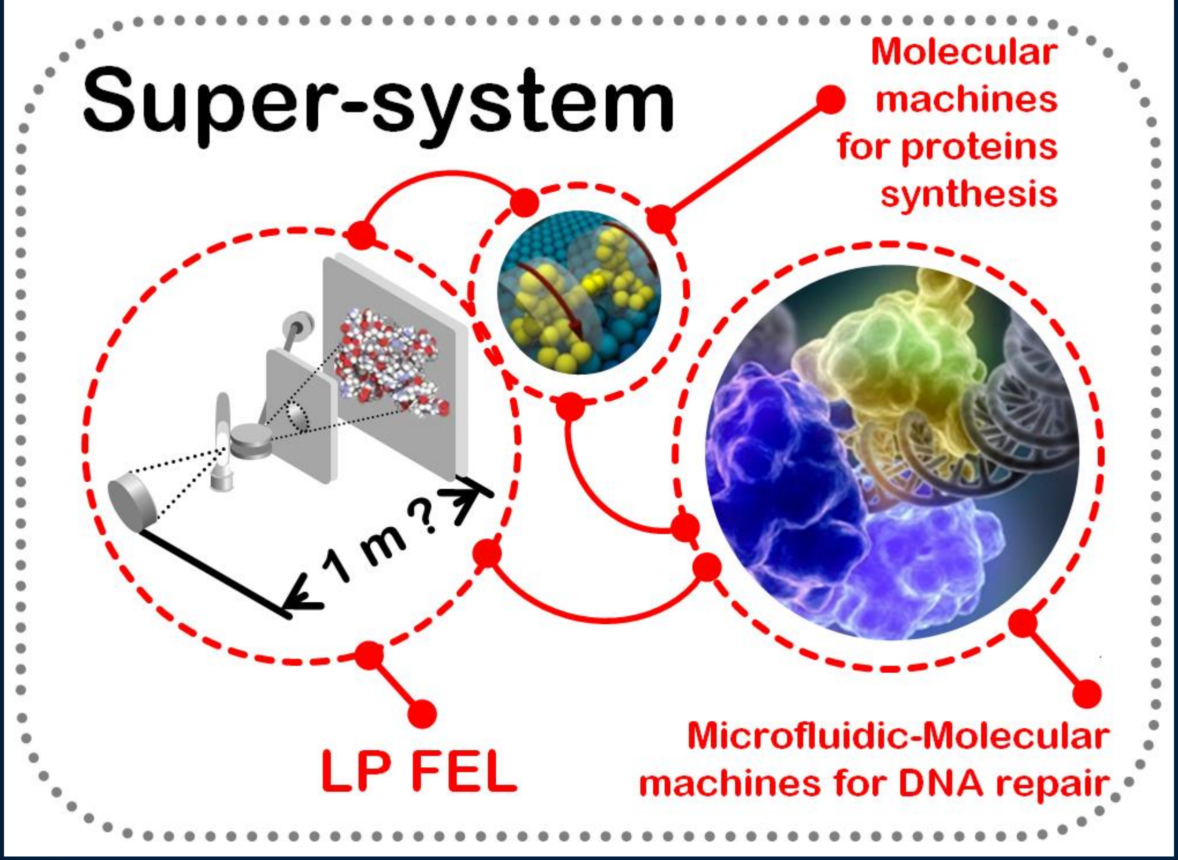
FEL and molecular machine becomes part of another system

FEL is part of system where it analyses proteins synthesized by molecular machine

FEL is part of super-system where it analyses proteins synthesized by molecular machine, while the entire super-system produces patient-tailored molecular machines for DNA repair



Make this dream – with help of Breakthrough By Design approach – a reality!



Laser plasma FEL is part of super-system where it analyses proteins synthesized by molecular machine, while the entire super-system produces patient-tailored molecular machines for DNA repair

“The greater danger for most of us lies not in setting our aim too high and falling short; but in setting our aim too low, and achieving our mark”

Michelangelo

In combination with the art of estimations, TRIZ can be very useful for university education and research

As an inspiration, as a very efficient toolbox, as a way to connect different disciplines, as a new way to see the world – **Breakthrough By Design approach**

Thank you for your attention!

And thanks to all colleagues for materials used in these slides

Questions?