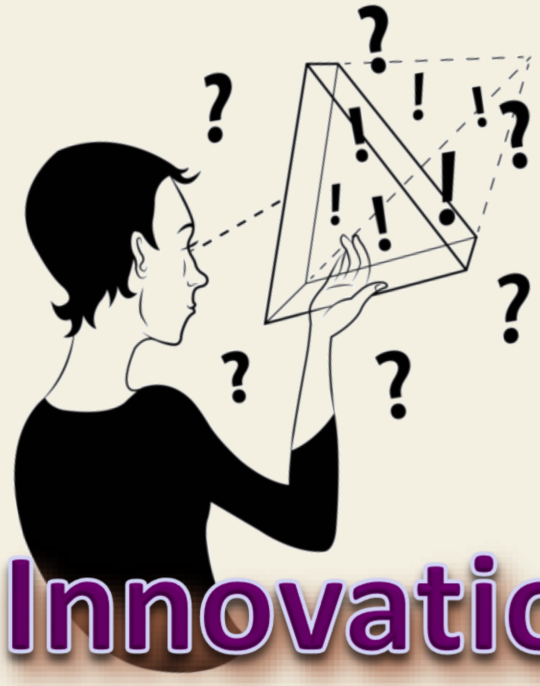
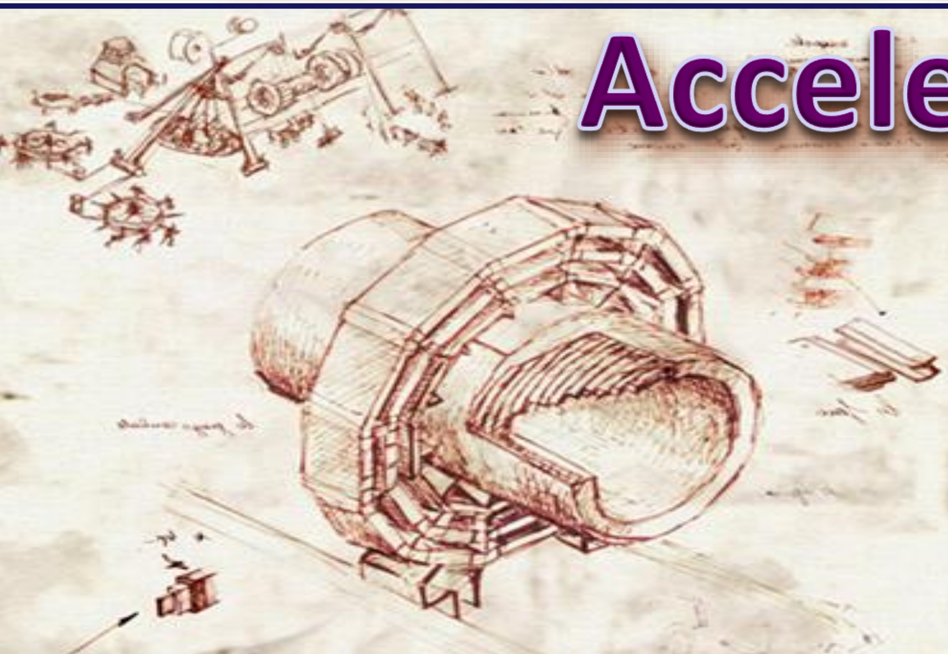
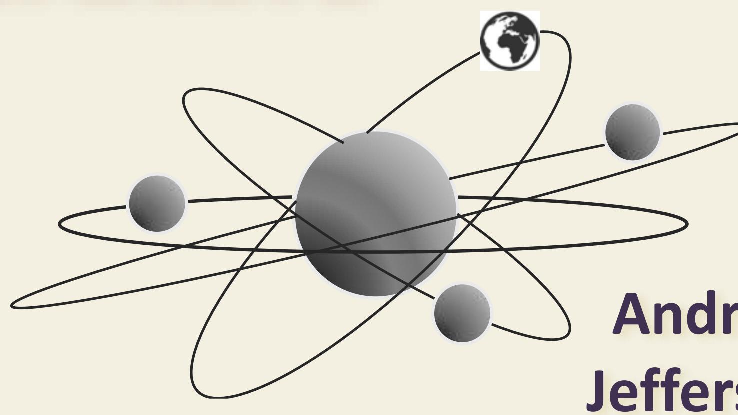
Innovation Techniques in Accelerators





LHC sketches by Sergio Cittolin (CERN)



Andrei Seryi
Jefferson Lab

International Accelerator School, Canada, Saskatoon
Lecture 03, 19 July 2023

Acknowledgements

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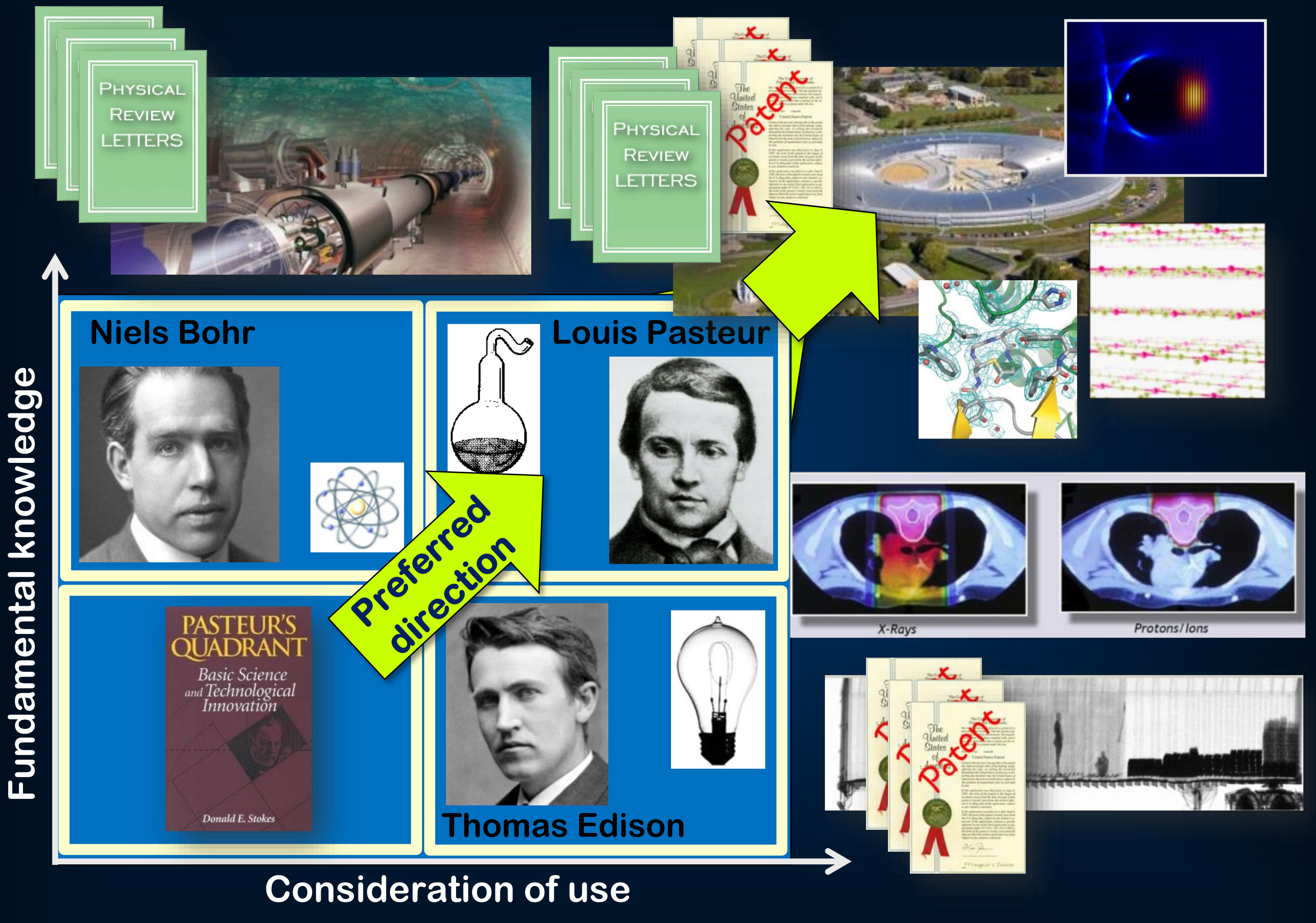
  - **Continuing support of graduate educational program**
- **Old Dominion University**
  - **Materials presented here are used as part of VITA graduate and undergraduate courses**
    - **VITA – Virginia Innovative Traineeship in Accelerators**
    - **ODU, NSU, HU – three universities – VITA**
- **My 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/

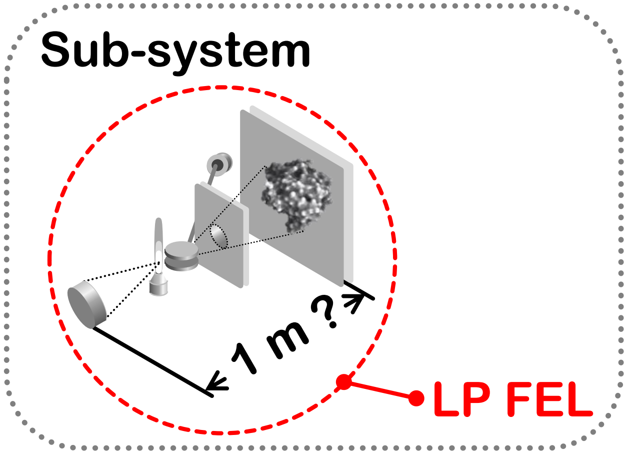
  - **See section Resources**
  - **You can also access the 1st edition of the book which is now Open Access**

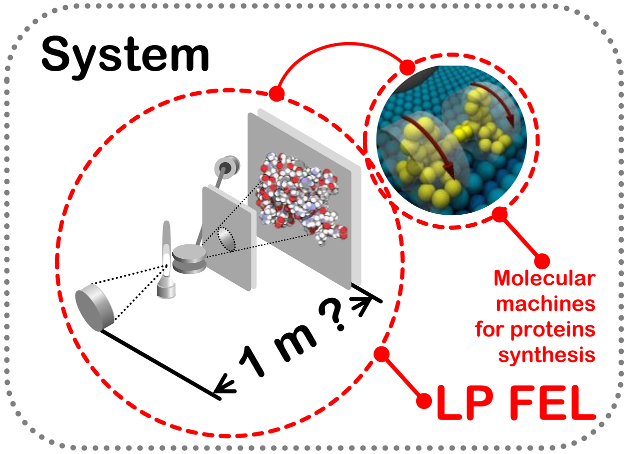

PHYSICAL REVIEW LETTERS
PHYSICAL REVIEW LETTERS
Patent
Niels Bohr
Louis Pasteur
Preferred direction
PASTEUR'S QUADRANT
Basic Science and Technological Innovation
Donald E. Stokes
Thomas Edison
X-Rays
Protons/Ions
Patent
Fundamental knowledge
Consideration of use

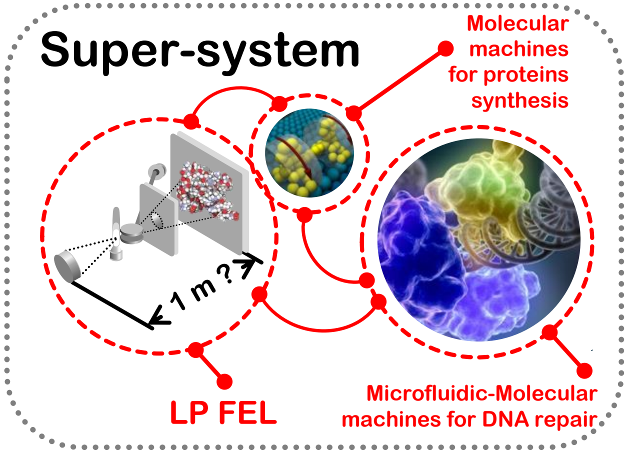
FEL and molecular machine becomes part of another system

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

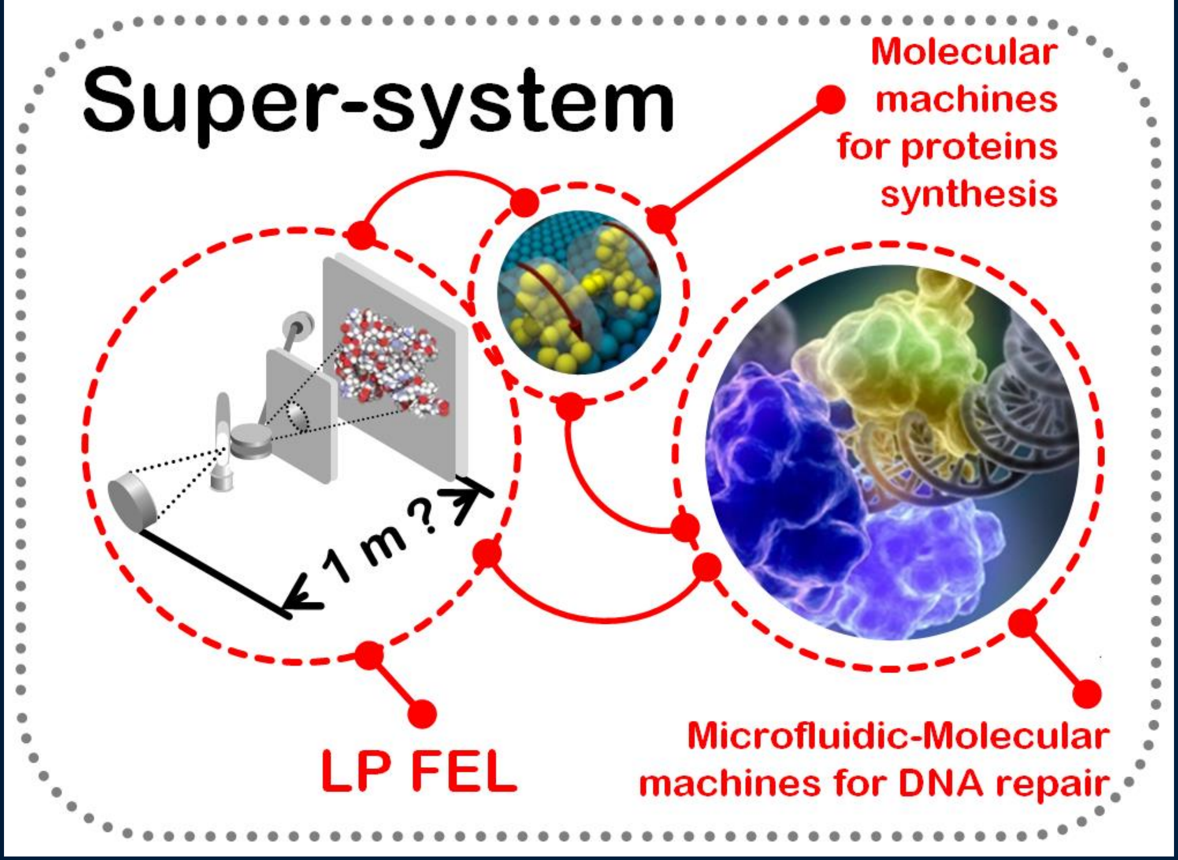
FEL is part of super-system where it analyses proteins synthesized by molecular machine, while the entire super-system produces patient-tailored molecular machines for DNA repair





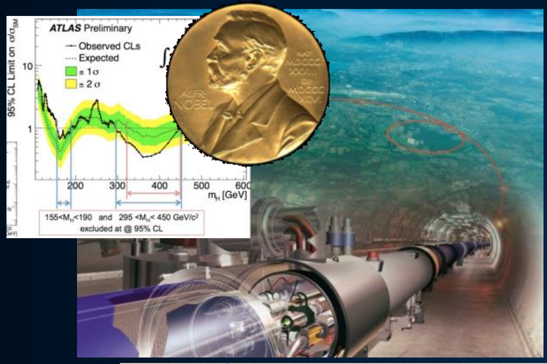


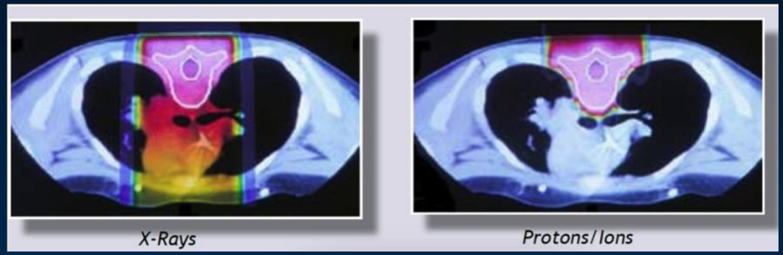
Make this dream – with help of Breakthrough By Design approach – a reality!

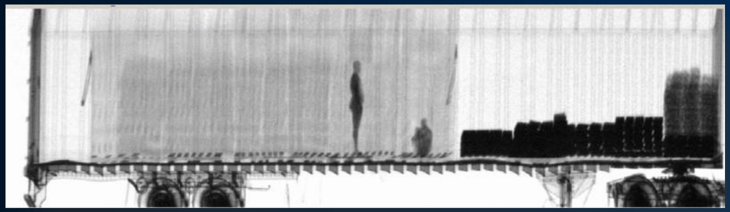


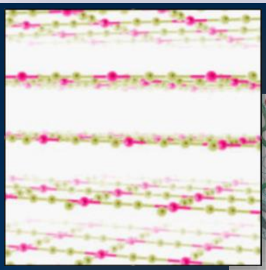
Laser plasma FEL is part of super-system where it analyses proteins synthesized by molecular machine, while the entire super-system produces patient-tailored molecular machines for DNA repair

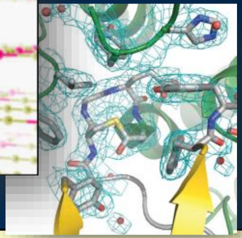
Accelerators for science and society











Accelerators: high energy physics, nuclear physics, healthcare, security, energy, life science, novel materials, industry…

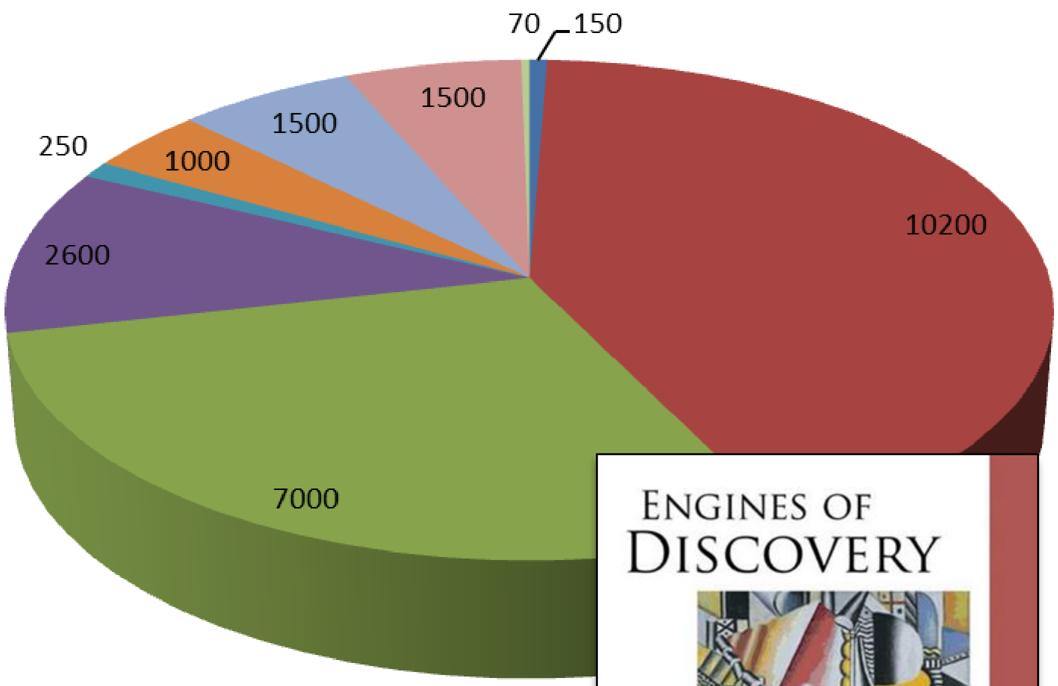
Tens of millions of patients receive accelerator-based diagnoses and treatment each year in hospitals and clinics around the world

All products that are processed, treated, or inspected by particle beams have a collective annual value of more than $500B

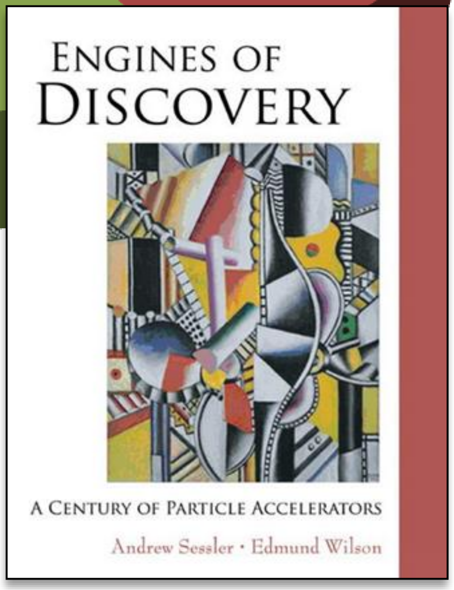
The fraction of the Nobel prizes in Physics directly connected to accelerators is about 30%

Accelerators in the world >30000

Not counting TVs ;-)



- High Energy Accelerators of more than 1 GeV
- Ion implantation
- Electron cutting and welding
- Electron beam and X-ray irradiators (sterilization)
- Ion Beam analysis (including AMS)
- Radioisotope production (including PET)
- Non destructive testing (including security)
- Neutron generators (including sealed tubes)
- Synchrotron radiation



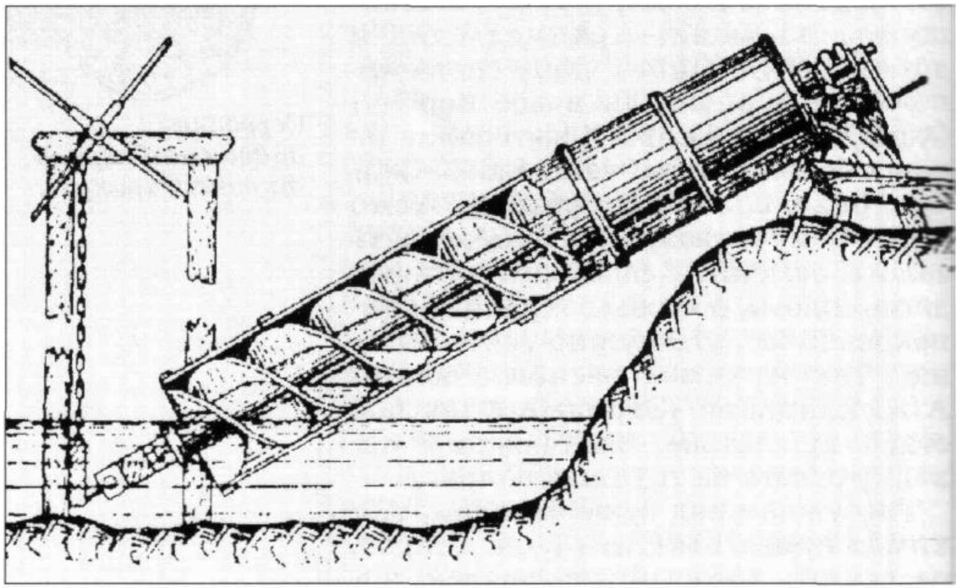
Engines of Discovery.
A Century of Particle Accelerators.
Andrew Sessler, Edmund Wilson

Source (2007):
http://www.worldscientific.com/worldscibooks/10.1142/6272

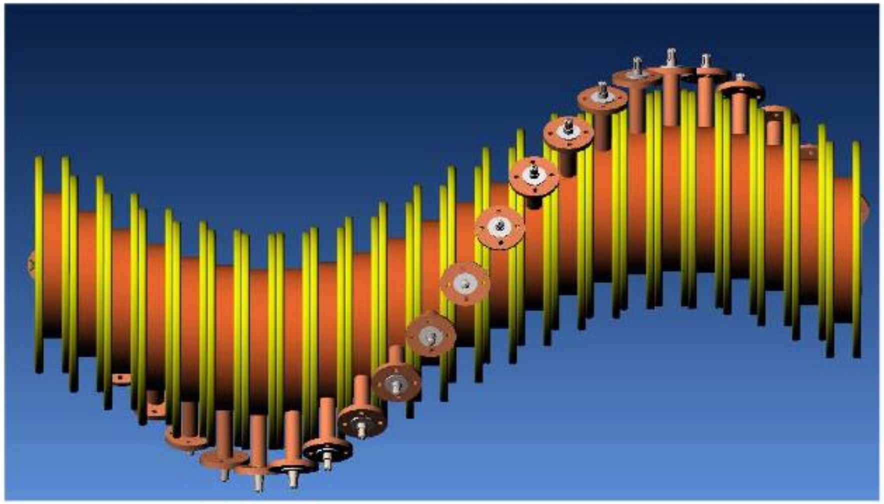
Accelerator science and inventions…

Accelerator science demonstrates rich history of inventions, often inspired by the nature itself

DNA



Muon Collider cooling channel … may have been inspired by the shape of DNA

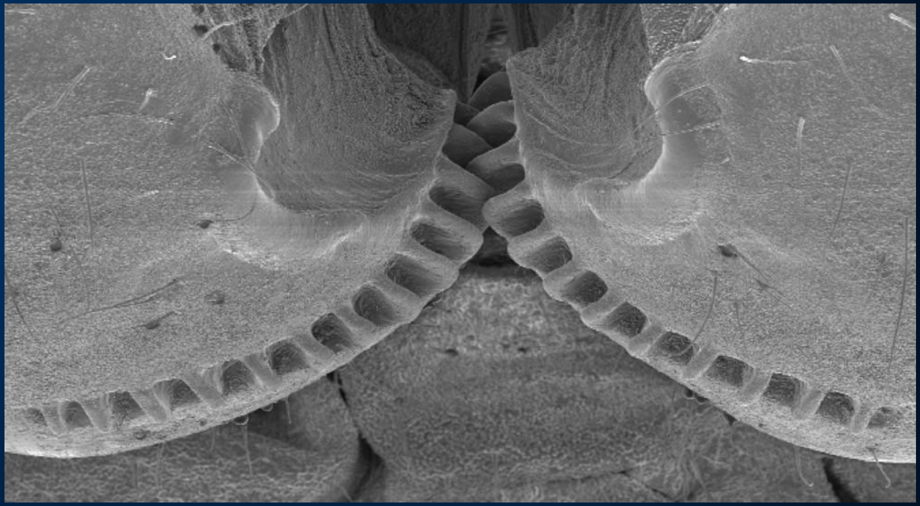


Integrated Helical Solenoid, absorbers and accelerating resonators

Motivation behind inventions

Technical inventions often inspired by nature itself (could be)

Were people the inventors of gears?



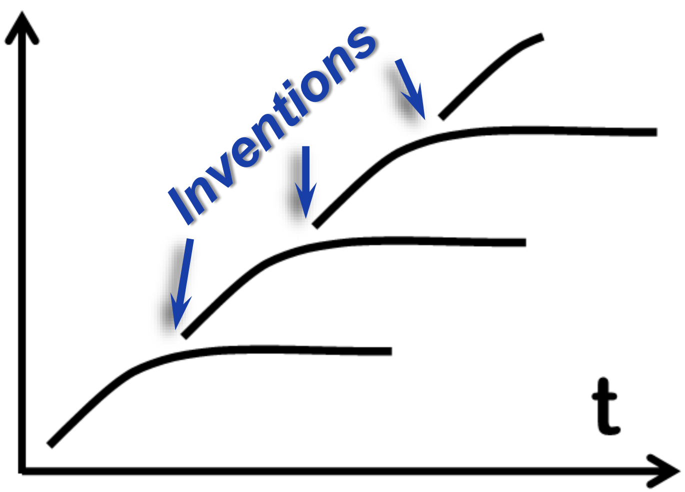
Insects have used them for millions of years!

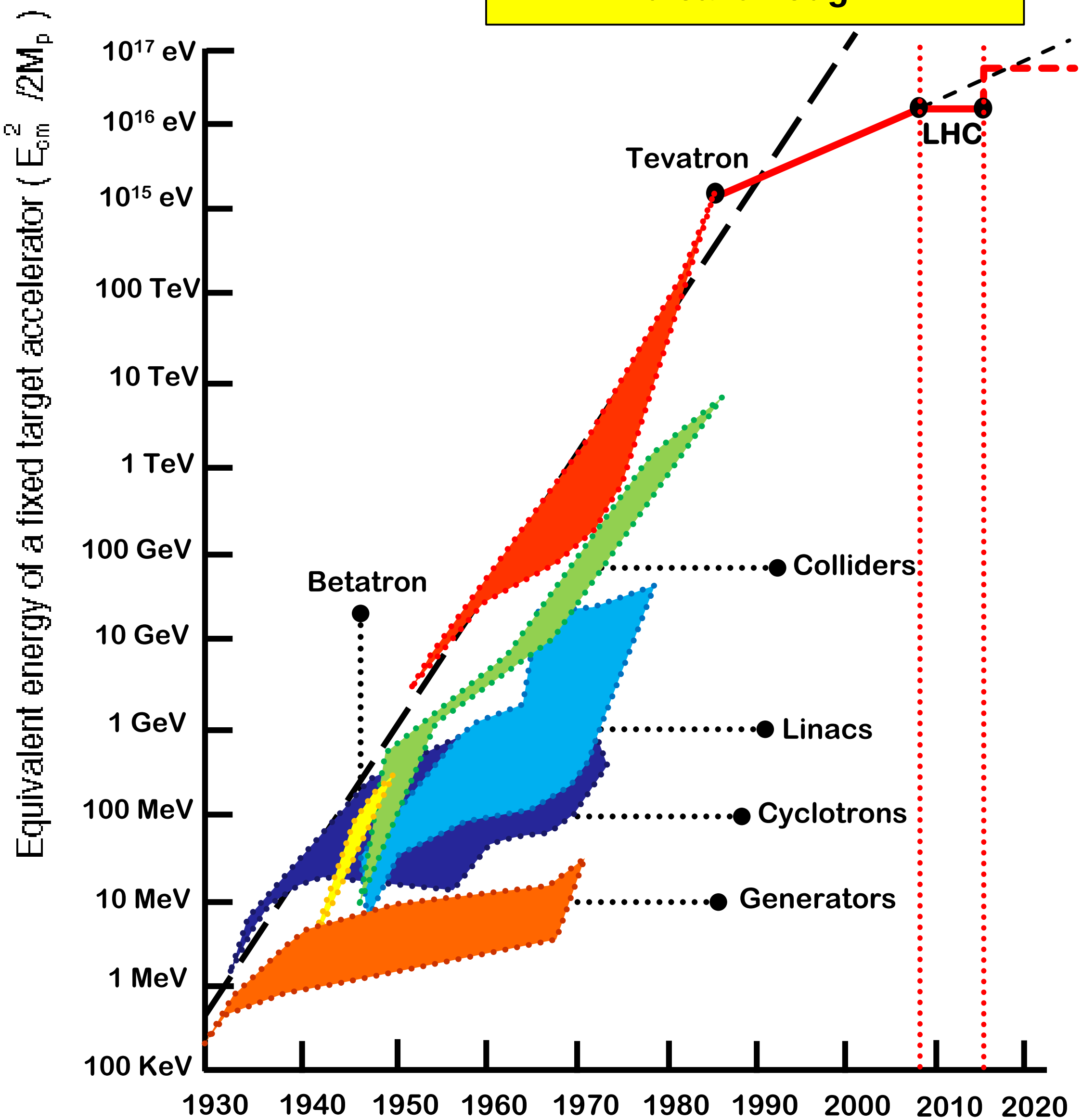
Interacting Gears Synchronize Propulsive Leg Movements in a Jumping Insect, Science, 13 Sep 2013, M.Burrows, G.Sutton

"Livingston plot"

Lasers and plasma may be necessary to make the next breakthrough

- **History of accelerators…**
- **…and evolution *(and saturation)* of particular technologies of acceleration, and birth of the new technologies *via inventions***





How to invent – TRIZ

Genrikh Altshuller
(aka Altov)1926-1998

- **TRIZ – *T*eoria *R*eshenia *I*zobretatelskikh *Z*adach**
= Theory of Inventive Problem Solving
- **Developed by Genrikh Altshuller in SU**
  - Work in patent office in 1946
  - Analysed many patents, discovered patterns and identified what makes a patent successful
  - Formulated TRIZ in 1956-1985
- **Four key discoveries of TRIZ:**
  - The same Problems and Solutions appear again and again but in different industries
  - There is a recognisable Technological Evolution path for all industries
  - Innovative patents (23% of total) used science/engineering theories outside their own area/industry
  - An Innovative Patent uncovers and solves contradictions

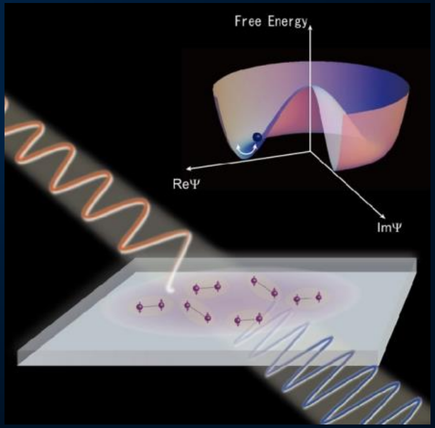
Discovery 2012, Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

Higgs and Superconductivity

"The recent discovery of the Higgs boson has created a lot of excitement … the theoretical proposal of the Higgs mechanism was actually inspired by ideas from condensed matter physics … In 1958, Anderson discussed the appearance of a coherent excited state in superconducting condensates with spontaneously broken symmetry... *On page 1145 of this issue, Matsunaga et al. report direct observation of the Higgs mode in the conventional superconductor niobium nitride (NbN) excited by intense electric field transients*."

Particle physics in a superconductor, A Pashkin & A Leitenstorfer Science 345, 1121 (2014)



Higgs and Superconductivity

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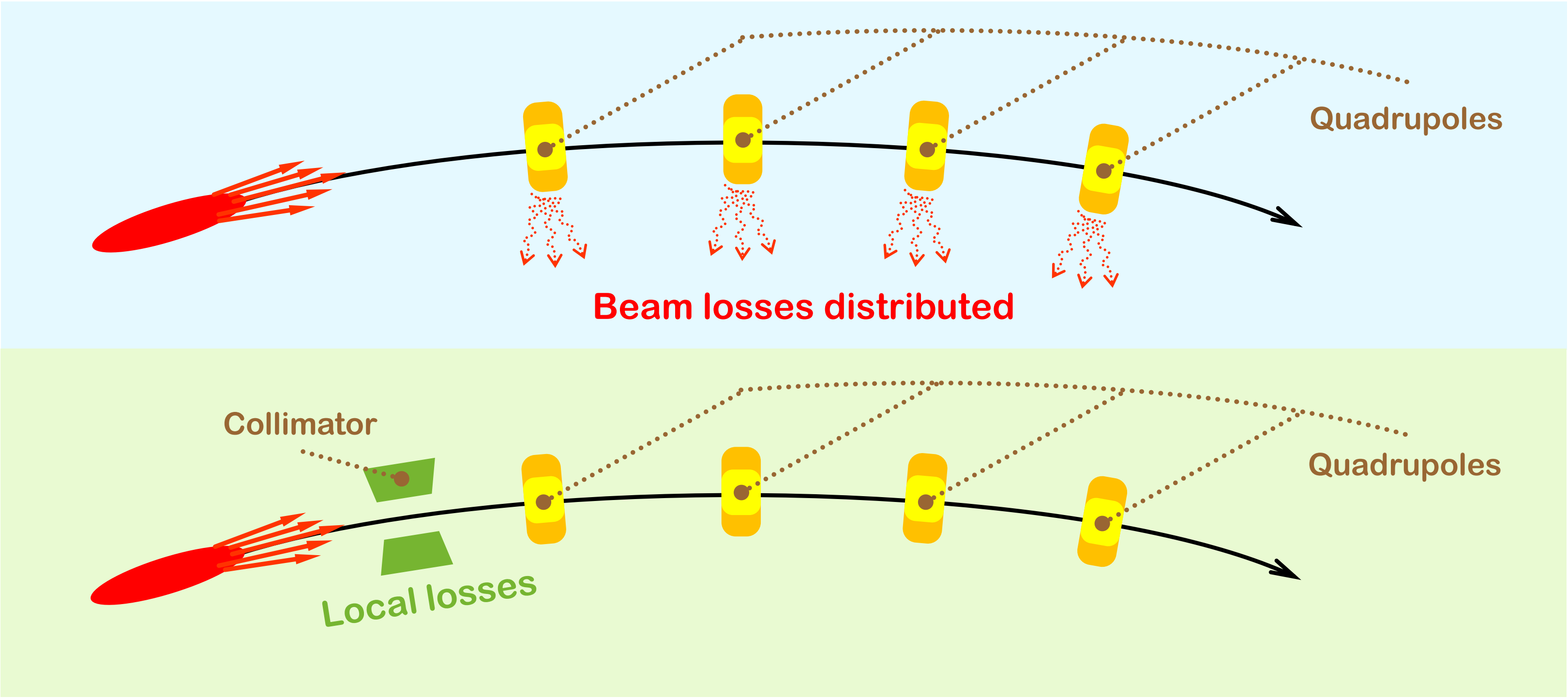
Particle physics in a superconductor, A Pashkin & A Leitenstorfer Science 345, 1121 (2014)

- This shows us that a general conclusion of TRIZ
  - ***“The same Problems and Solutions appear again and again but in different disciplines”***
- is applicable to science too

2.Taking out

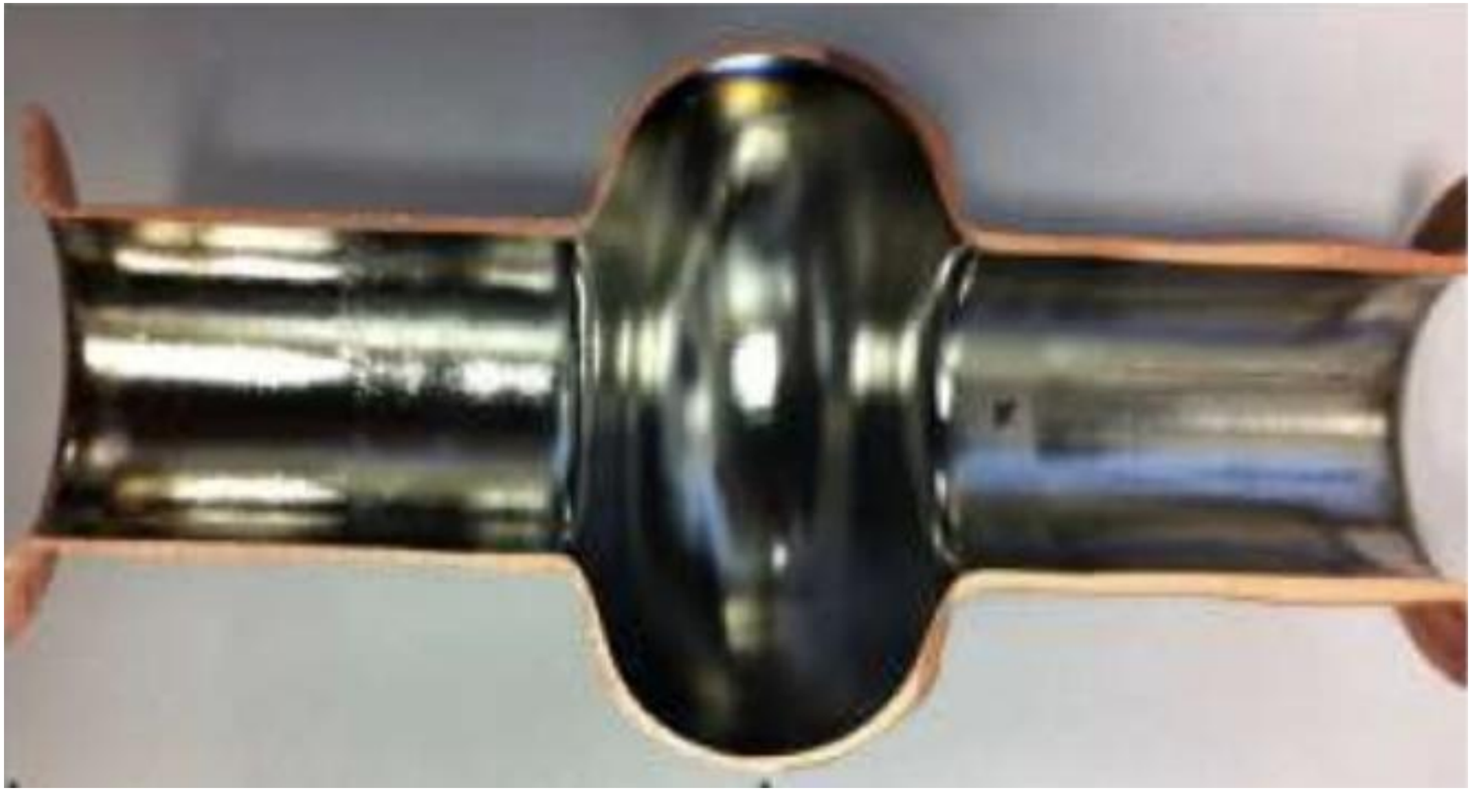
- Separate an interfering part or property from an object;
- Single out the only necessary part (or property) of an object.



Collimation of the beam to localize beam losses

3. Local quality

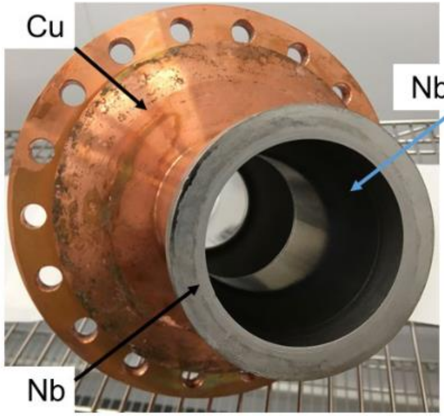
- **Change an object's structure from uniform to non-uniform, change an external environment (or external influence) from uniform to non-uniform.**
- **Make each part of an object function in conditions most suitable for its operation.**
- **Make each part of an object fulfill a different and useful function.**

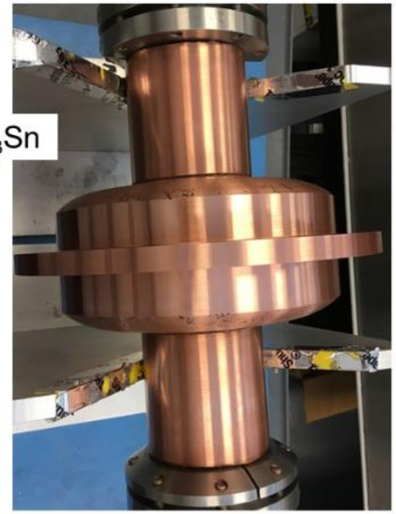


Nb coated copper cavity

Enzo Palmieri, A.A.Rossi, R. Vaglio, "Experimental Results on Thermal Boundary Resistance for Nb and Nb/Cu", Science, Oct 2014

Cu-Nb-Nb_3Sn cavities & TRIZ #3 local quality

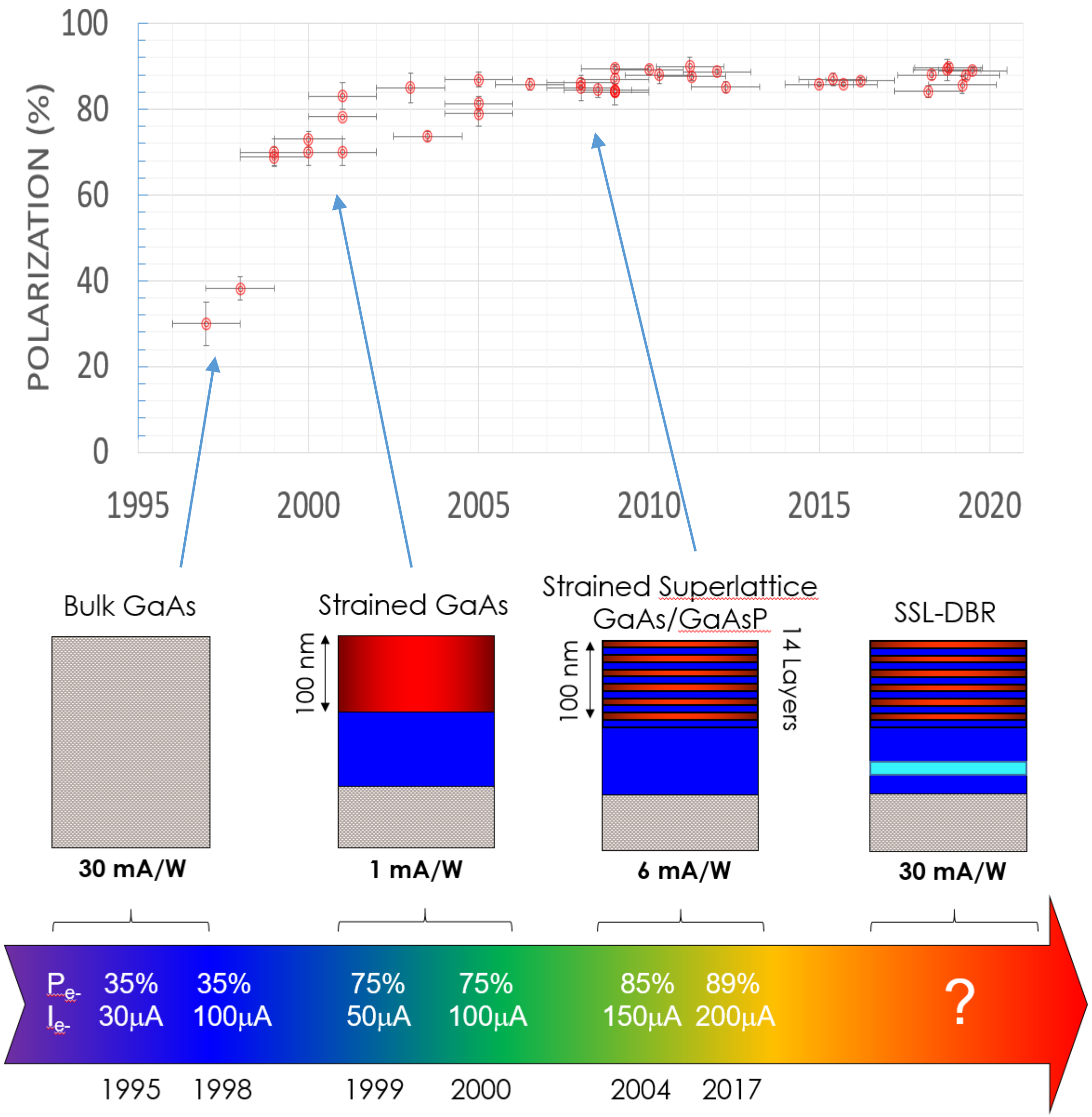




- **Efforts toward conduction-cooled cavities**
  - **Nb cavities covered outside with Cu, and inside with Nb3Sn**
  - **Can work at 4K**
  - **Cu provide thermal sink**
  - **Suitable for cryo-coolers, stand-alone compact linac for applications**
  - **Efforts at FNAL, Cornell, Jefferson Lab, Euclid**

G. Ciovati, G. Cheng, U. Pudasaini, R. Rimmer, Supercond. Sci. Technol. 33, 07LT01 (2020)
R. Dhuley et al., IOP Conf. Ser.: Mater. Sci. Eng. 755, 012136 (2020)

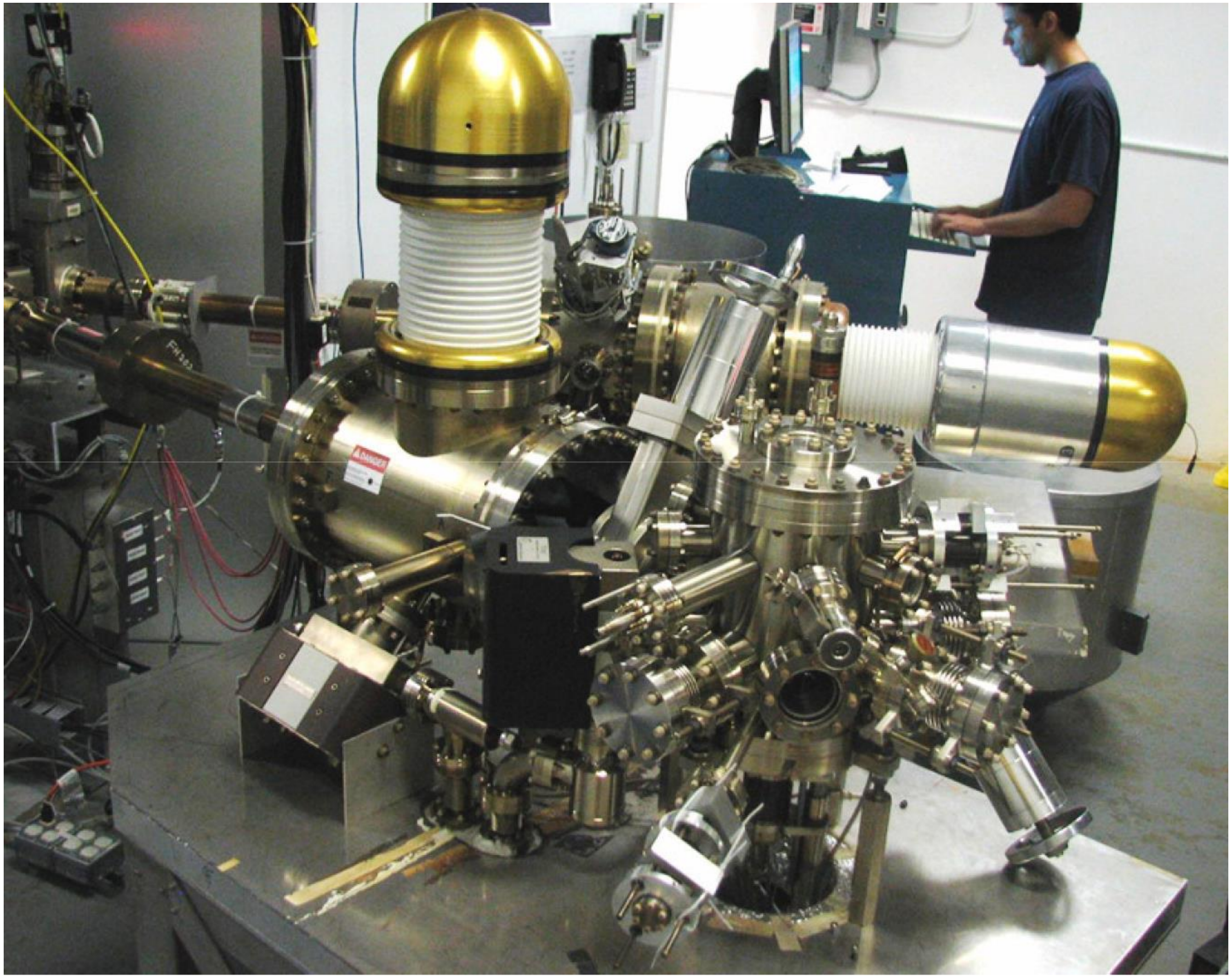
#3 Local Quality & Improving Polarized Source Performance



- **Technology advances for e-beam polarization improvements**
- **New experiments demanded longer lifetime of cathodes and new design of guns**
- **ILC played a stimulating role for development of new ILC/CEBAF "Inverted gun"**

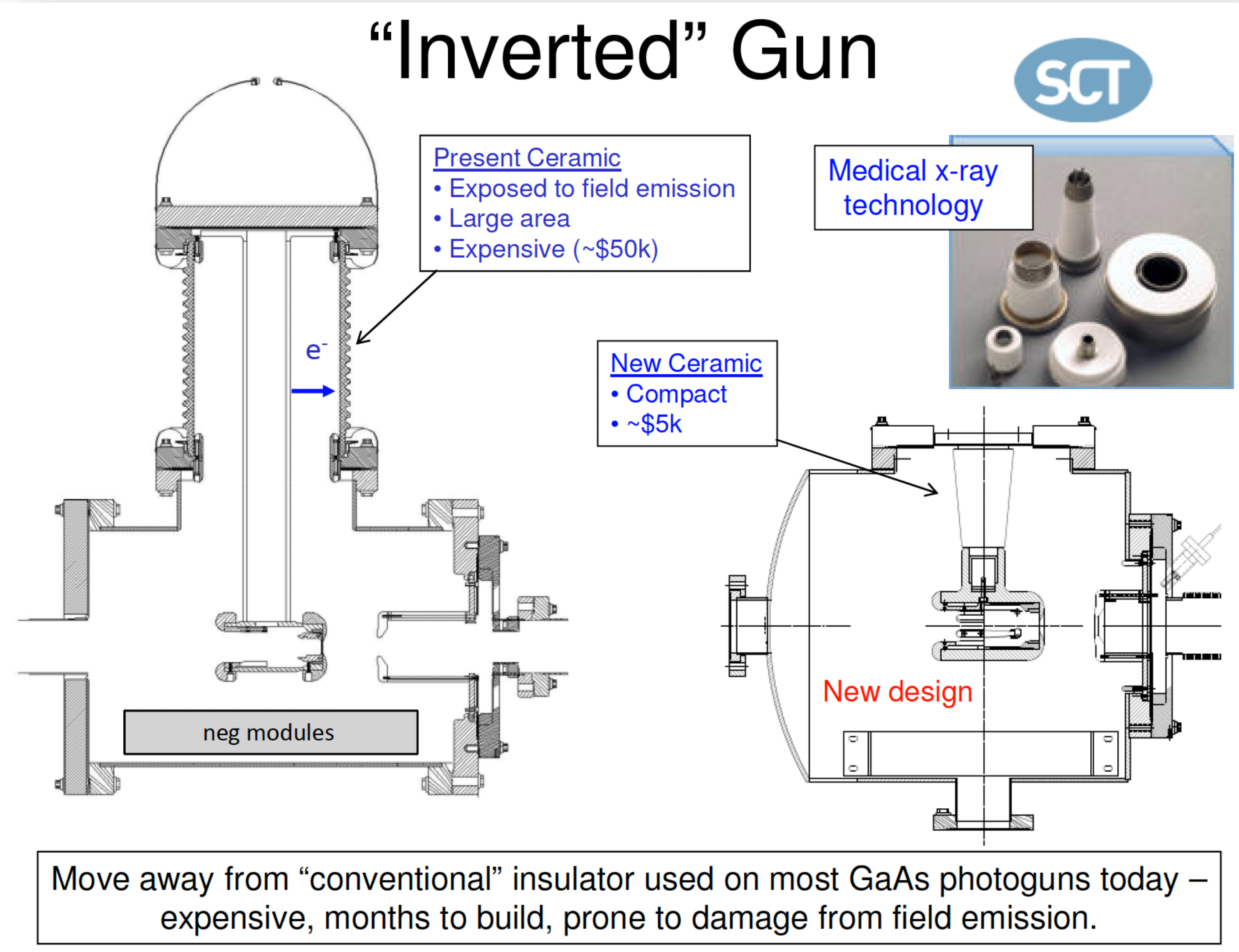
Inventive principle #3 "Local quality"

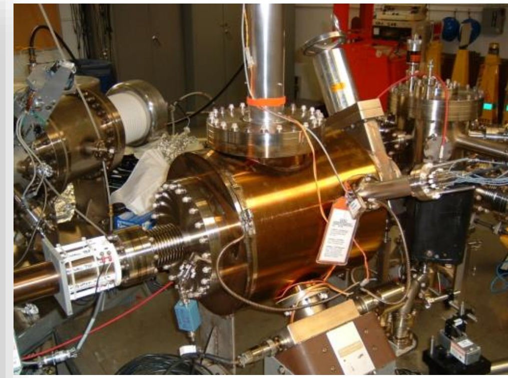
CEBAF load-lock polarized gun – installed in 2007



100kV gun. Lifetime limited to 30C. Path to higher lifetime and beam quality – higher voltage

#13 – New CEBAF/ILC "Inverted" gun ~2007-2009





Inverted CEBAF/ILC Gun#1 installed at CEBAF, July 2009

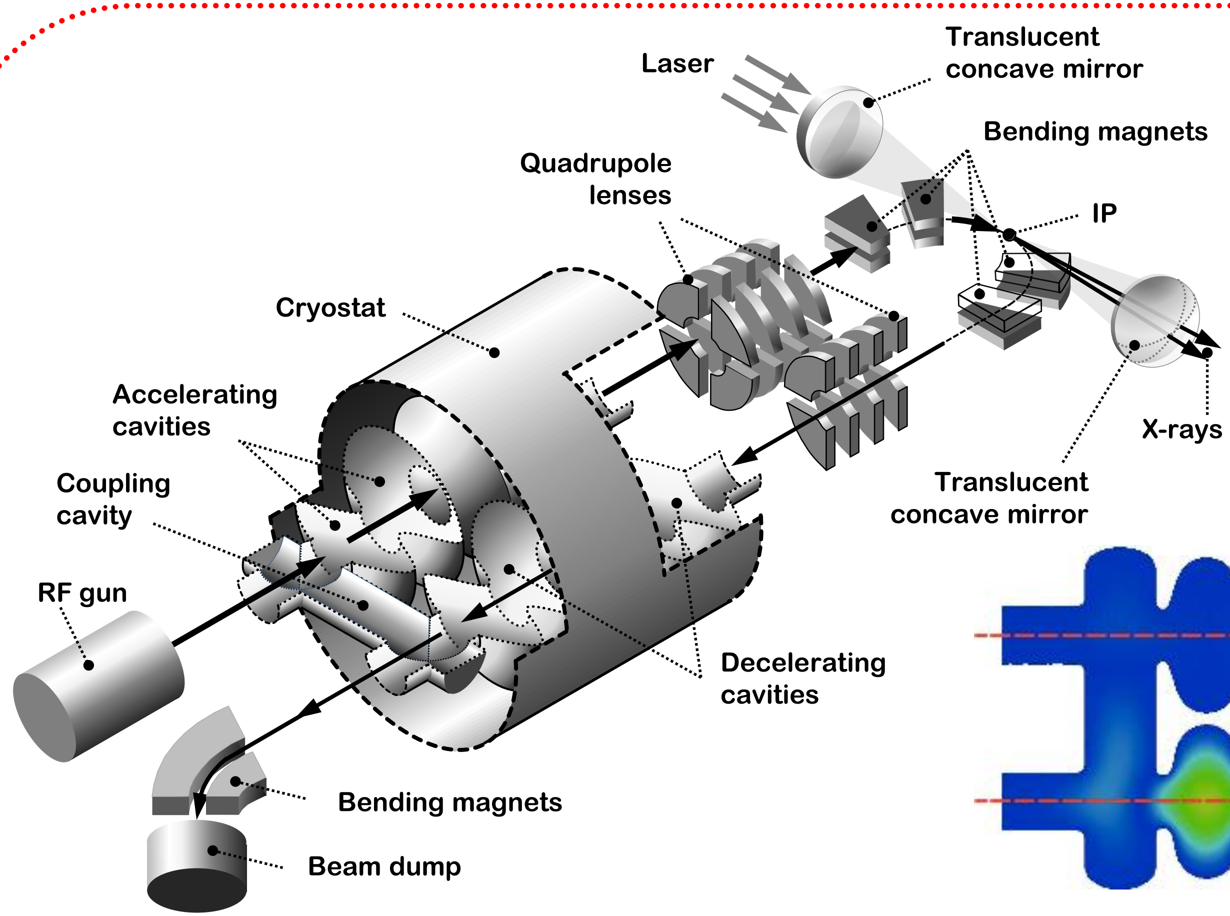
Higher voltage, higher lifetime

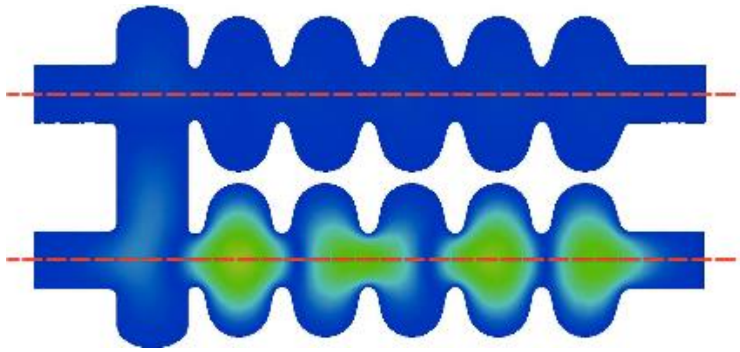
200 kV for CEBAF, 350 kV for ILC

Inventive principle #13
"The other way around"

4. Asymmetry

- Change the shape of an object from symmetrical to asymmetrical.
  - If an object is asymmetrical, increase its degree of asymmetry.





Cavities are slightly different to resonate on the main mode but be decoupled for all higher order modes

R. Ainsworth, G. Burt, I. V. Konoplev, A. Seryi, arXiv:1509.03675, 2015

5. Merging

- Bring closer together (or merge) identical or similar objects, assemble identical or similar parts to perform parallel operations.
- Make operations contiguous or parallel; bring them together in time.

Single-channel and
Multi-channel (8- and 12-) pipettes

96- or 384-channel Modular Dispense Technology™ (MDT) dispense heads. PerkinElmer Janus.

Illustration: PerkinElmer

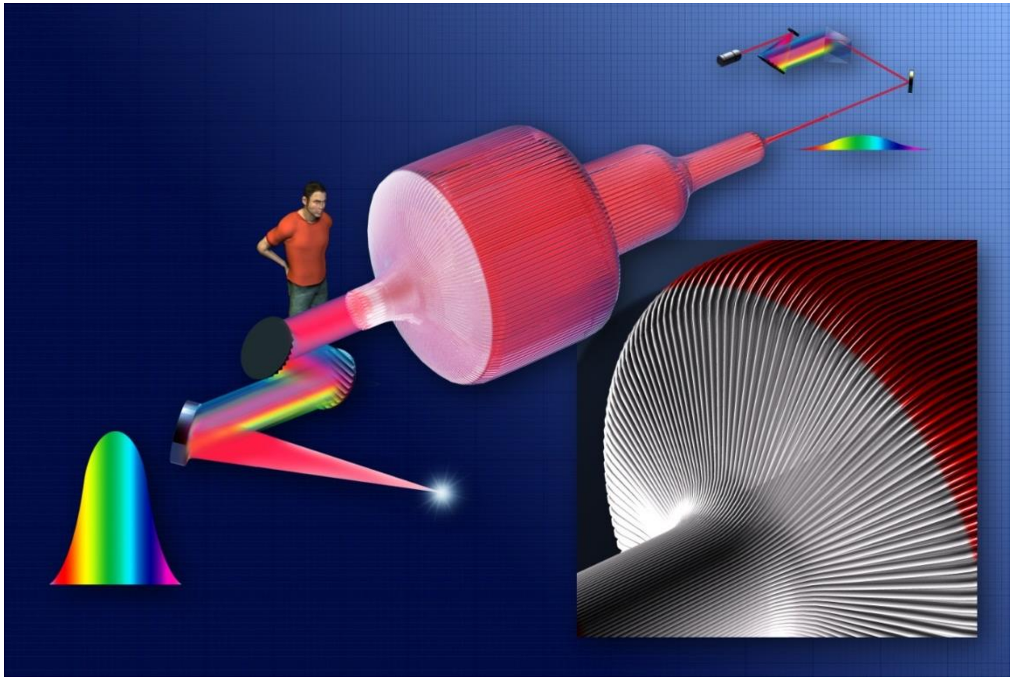
#5 Merging – and fiber lasers combination

- Commercial fiber lasers reach 100 kW in CW
- Wall plug efficiency > 40%
- But low energy pulsed or per fiber

Research on combining many fibre lasers (short pulses!) together for high rep rate, high energy laser systems.

Xcan
Coherent Amplification Network
POLYTECHNIQUE / THALES

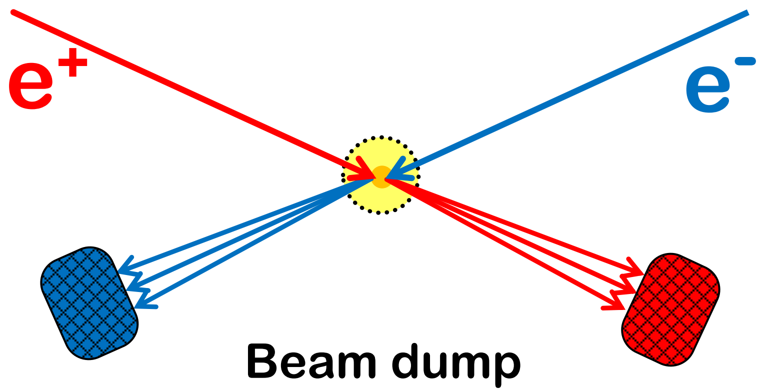
Phase control and combine 100s – 1000s fibres



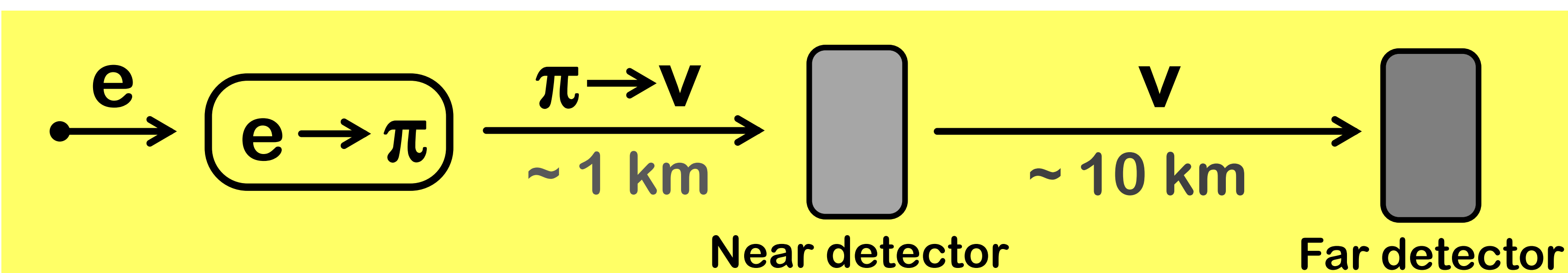
"The future is fibre accelerators", Gerard Mourou, Bill Brocklesby,Toshiki Tajima & Jens Limpert, Nature Photonics 7, 258–261 (2013)

6. Universality

- **Make a part or object perform multiple functions; eliminate the need for other parts.**



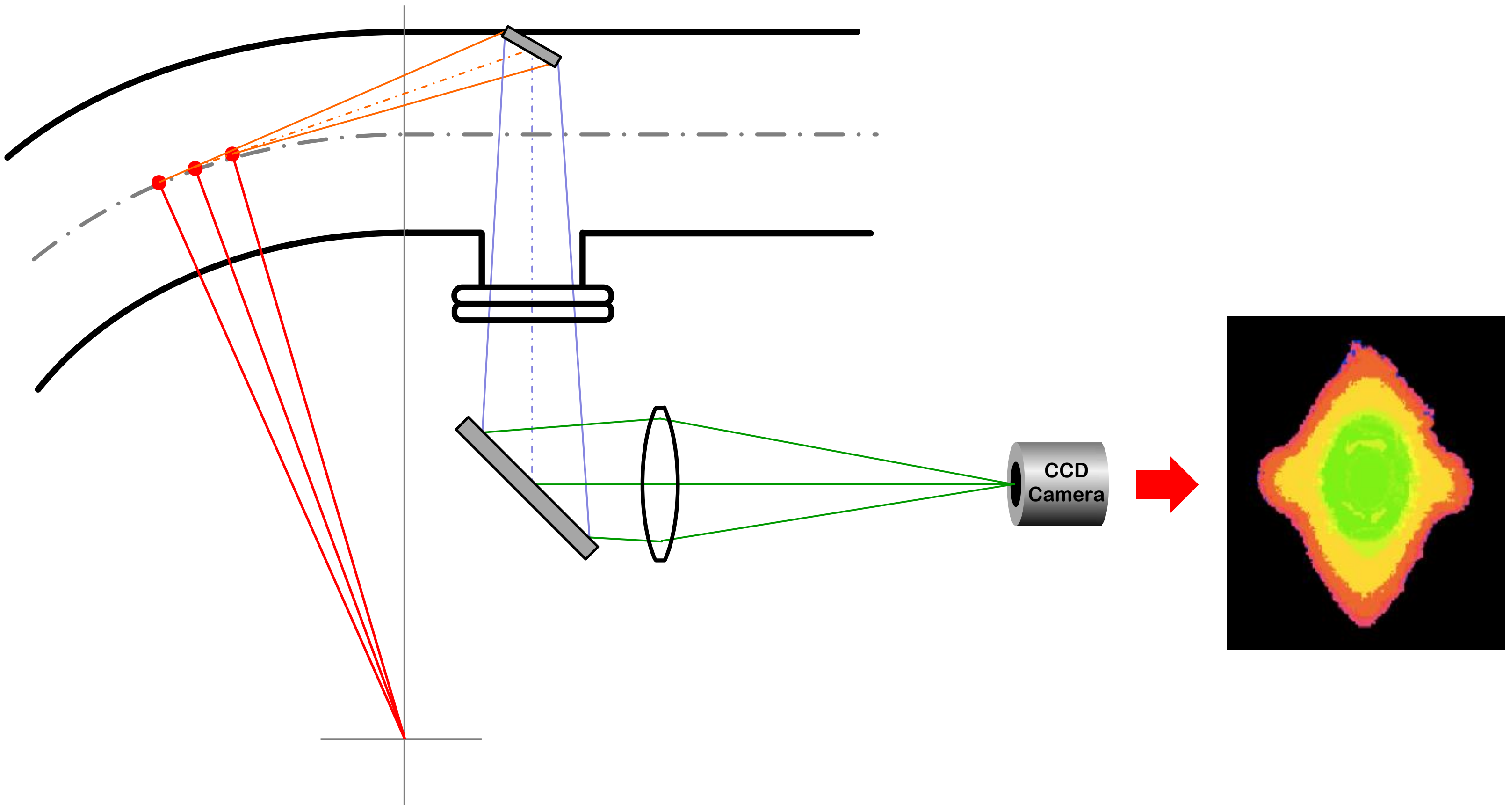
Make beam dump of linear collider to be sub-critical reactor to generate power or make neutrino factory out of it



I.F. Ginzburg, arXiv:1411.3295, 2014

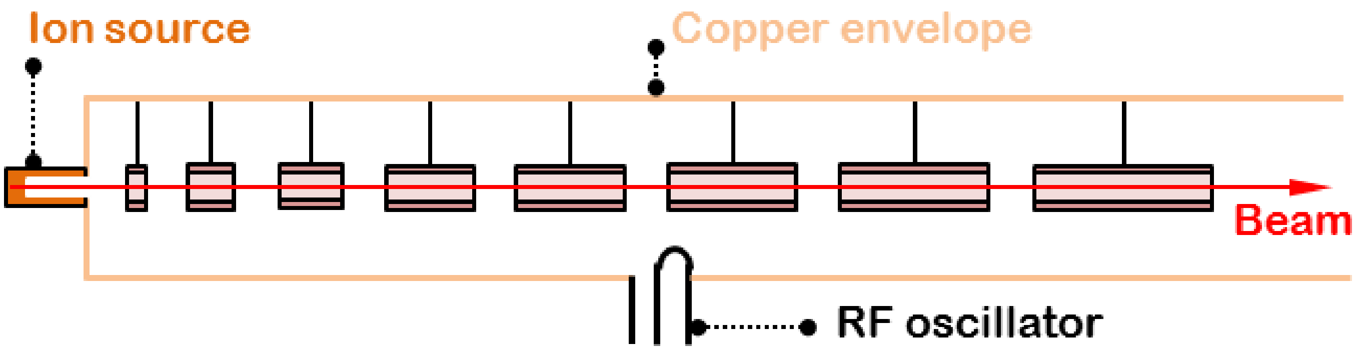
26. Copying

- Instead of an unavailable, expensive, fragile object, use simpler and inexpensive copies.
- Replace an object, or process with optical copies.
- If visible optical copies are already used, move to infrared or ultraviolet copies.



Synchrotron radiation profile monitor

Drift tubes - Alvarez Structure

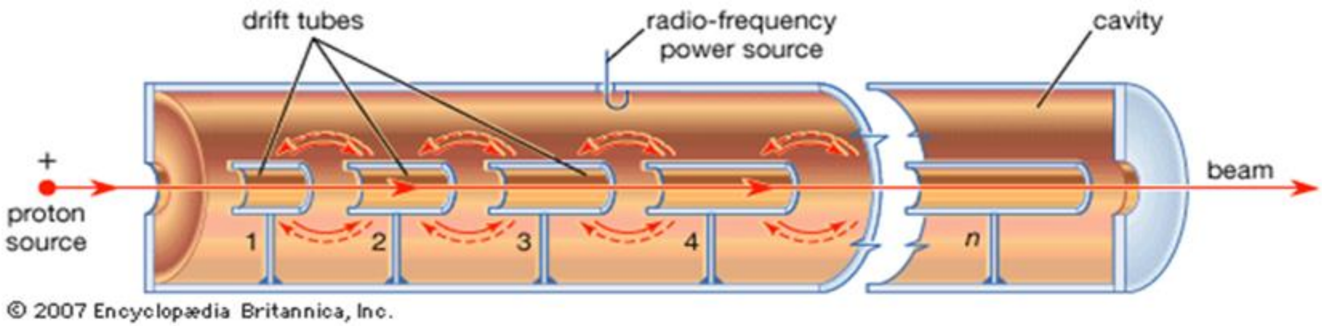


- Alvarez structure
  - Drift tubes are today arranged in a tank, made of good conductor (Cu), in which a cavity wave is induced

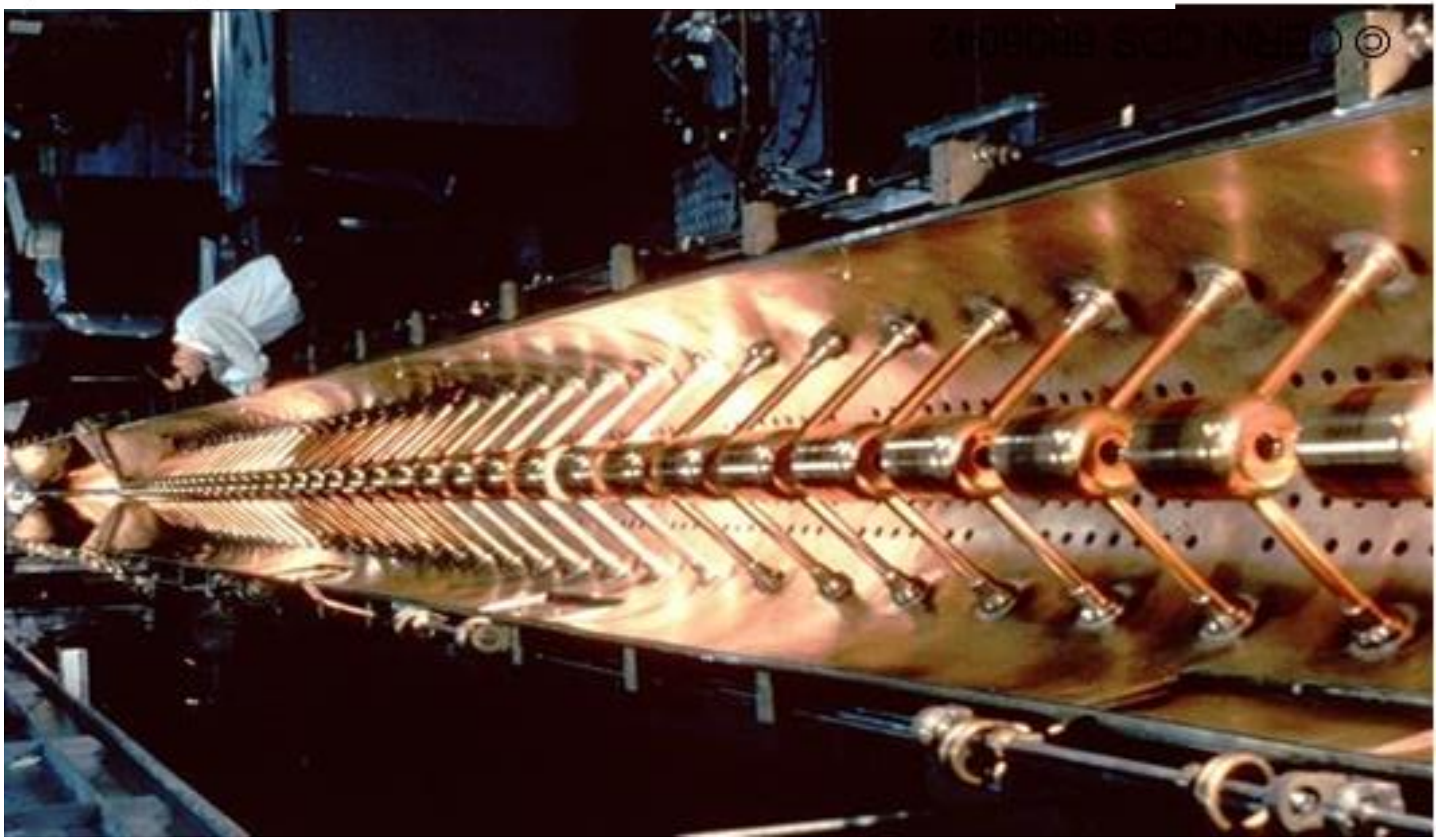
Re-inventing drift tube linac:
If you would need focusing elements in drift tube linac, where would you put them?

Drift tube linac - SuperHilac (Super Heavy Ion Linear Accelerator) LBNL

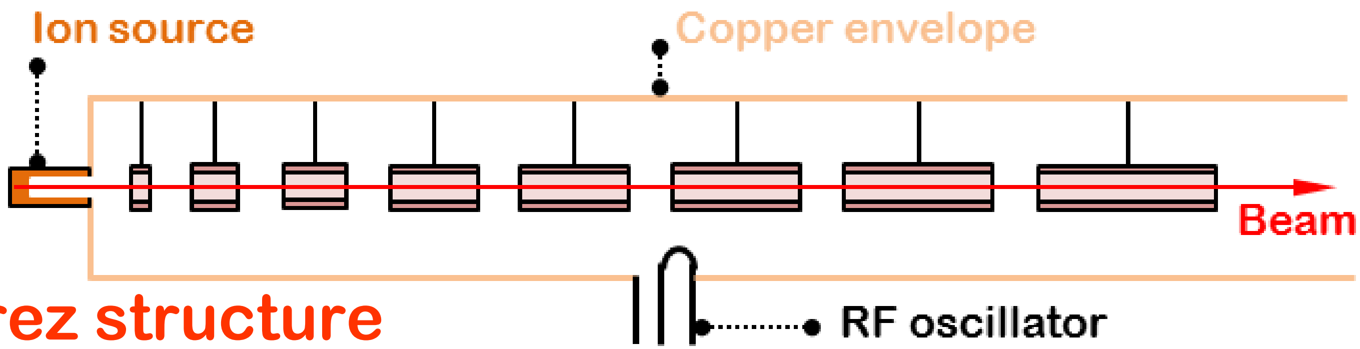
Drift Tube Linac examples



CERN LINAC1 1982-1992



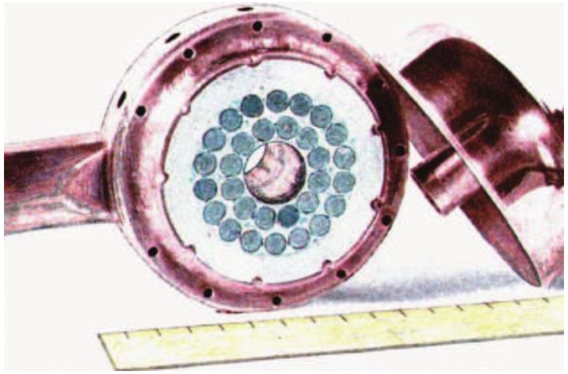
Drift tubes - Alvarez Structure



Alvarez structure

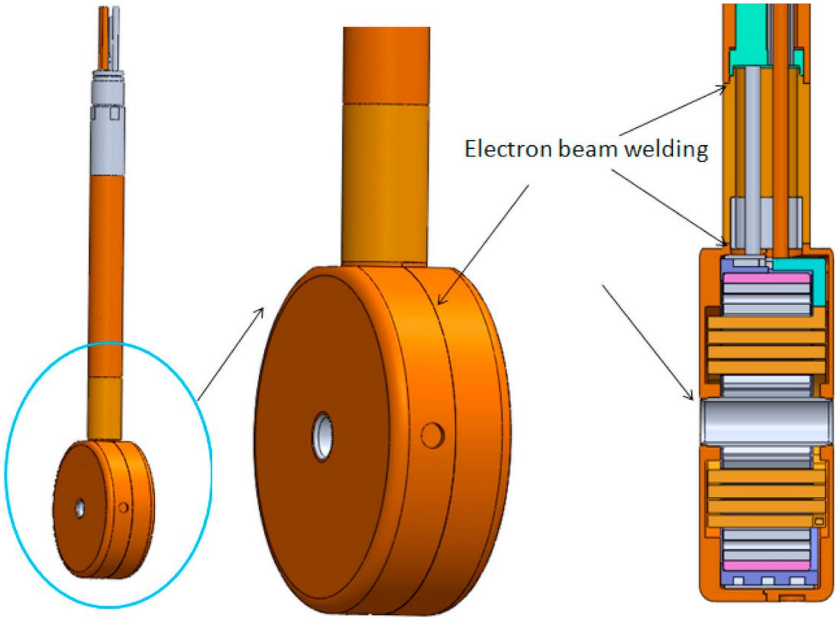
Drift tubes are today arranged in a tank, made of good conductor (Cu), in which a cavity wave is induced

The drift tubes, which have no field inside them, can also contain the magnets to focus the beam – "nested doll"



Drift tubes with permanent magnet focusing in ITEP's XADS

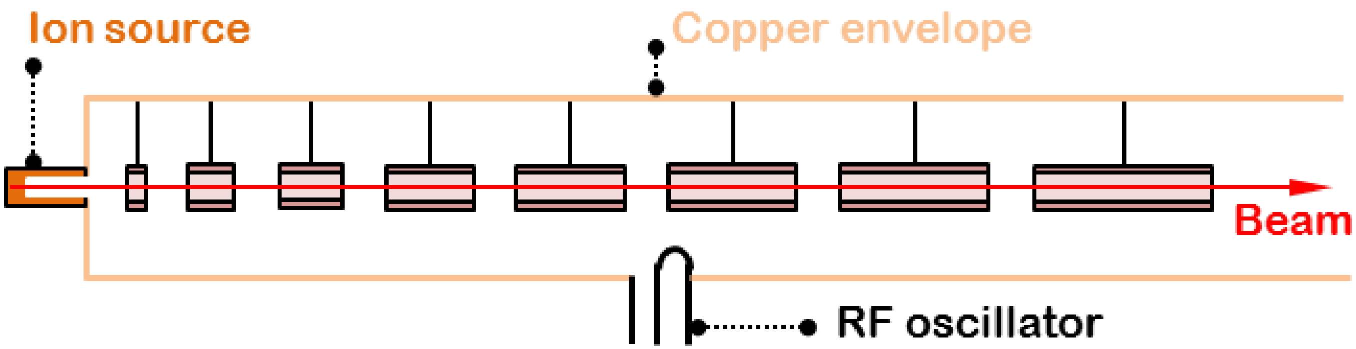
https://link.springer.com/article/10.1007/s12043-007-0028-2



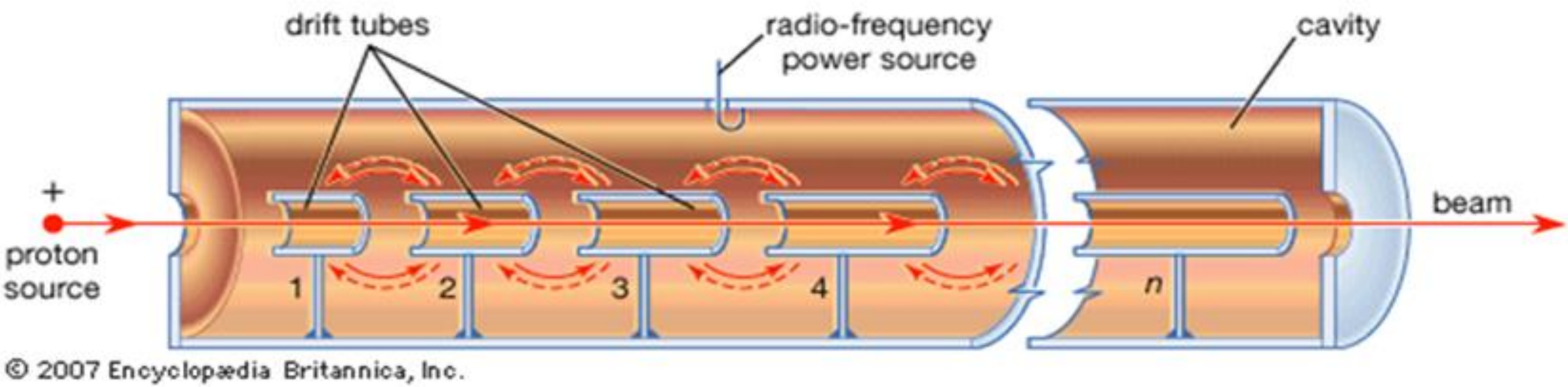
CSNS drift tube design – with electromagnetic focusing

https://www.sciencedirect.com/science/article/pii/S0168900218313482

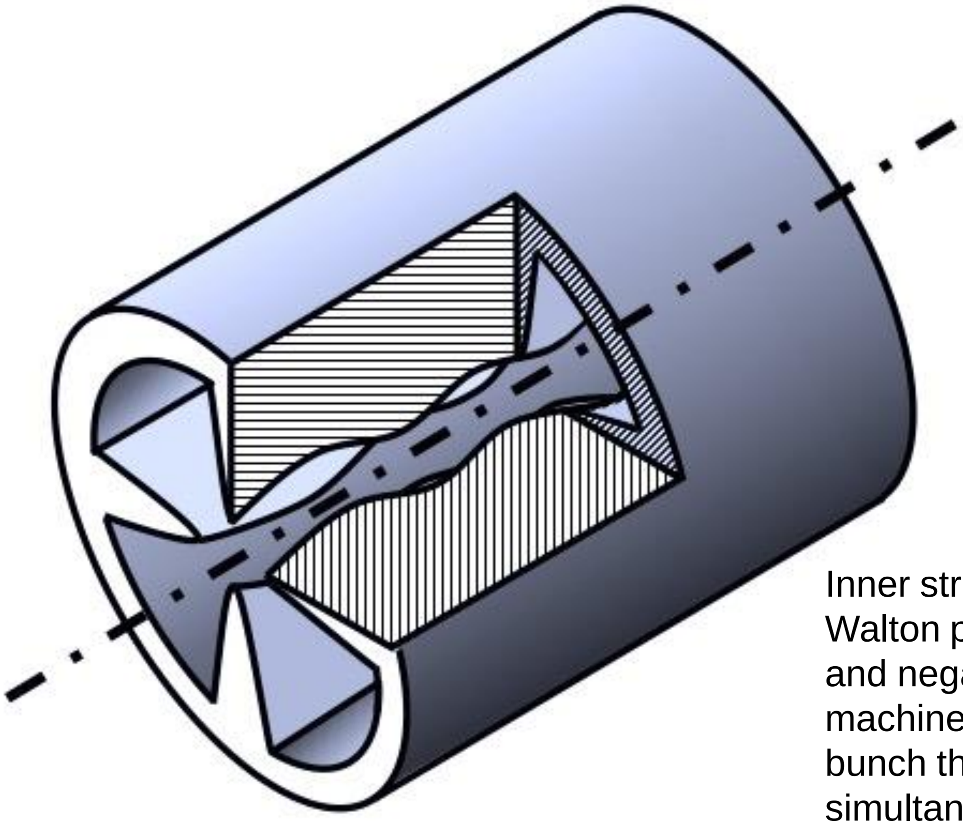
Re-inventing drift tubes like accelerator

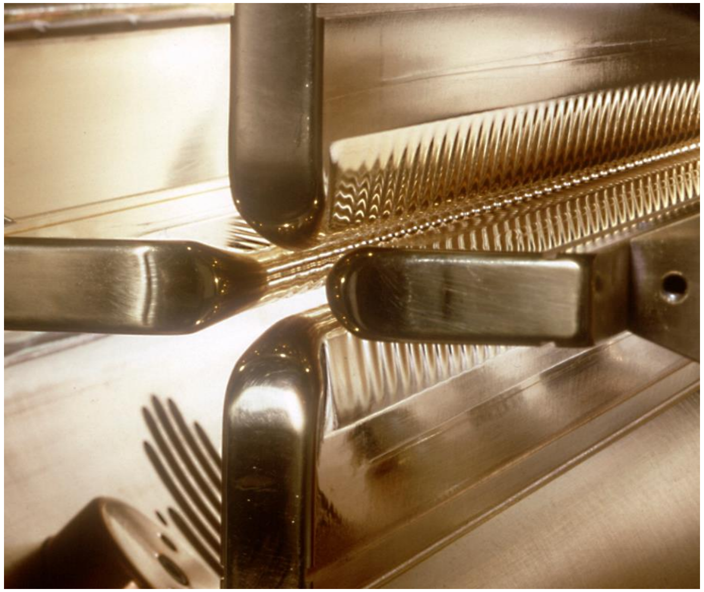


- Imagine that you need to add focusing to the drift-tube beamline
- We discussed placing magnets inside of the drift tubes
- Is there another method to add focusing?



RFQ accelerating structure

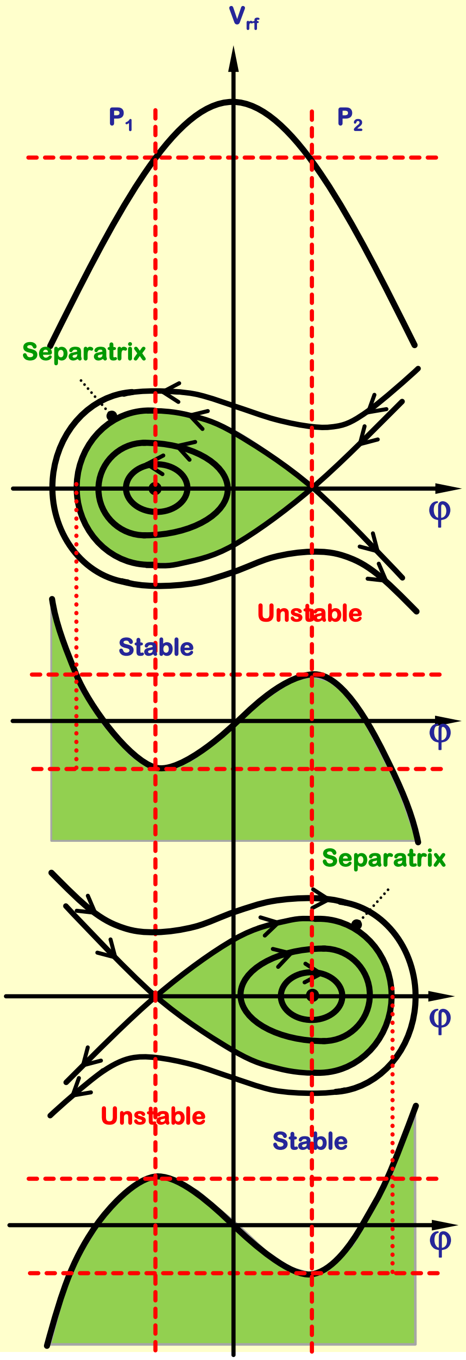




Inner structure of RFQ-1, which replaced in 1983 the Cockcroft-Walton preinjector of Linac 1 at CERN. It accelerated protons and negative hydrogen ions to 520 keV. The precision-machined modulated electrodes ("vanes") are shaped to first bunch the dc-beam from the ion source and then provide simultaneous acceleration and focusing of the beam.

http://cds.cern.ch/record/615852

Drift tubes linacs in modern accelerators for protons or ions are now typically replaced by RFQ – radio frequency quadrupole structures, that combine acceleration and focusing - *"going to another dimension"*



Re-inventing synchrotron

Period of revolution and energy connected as

$$\frac{dT}{T} \sim \left(\alpha_c - \frac{1}{\gamma^2}\right)\frac{dE}{E}$$

And thus "transition energy" is given by

$$\gamma_t = \frac{1}{\alpha_c^{1/2}} \qquad \textbf{where} \qquad \alpha_c = \frac{dC/C}{dp/p} = \frac{1}{C}\oint \frac{D(s)}{\rho(s)} ds$$

To keep the beam stable during acceleration, one need to switch the phase of RF, while passing the "transition energy". Still, some beam losses may occur.

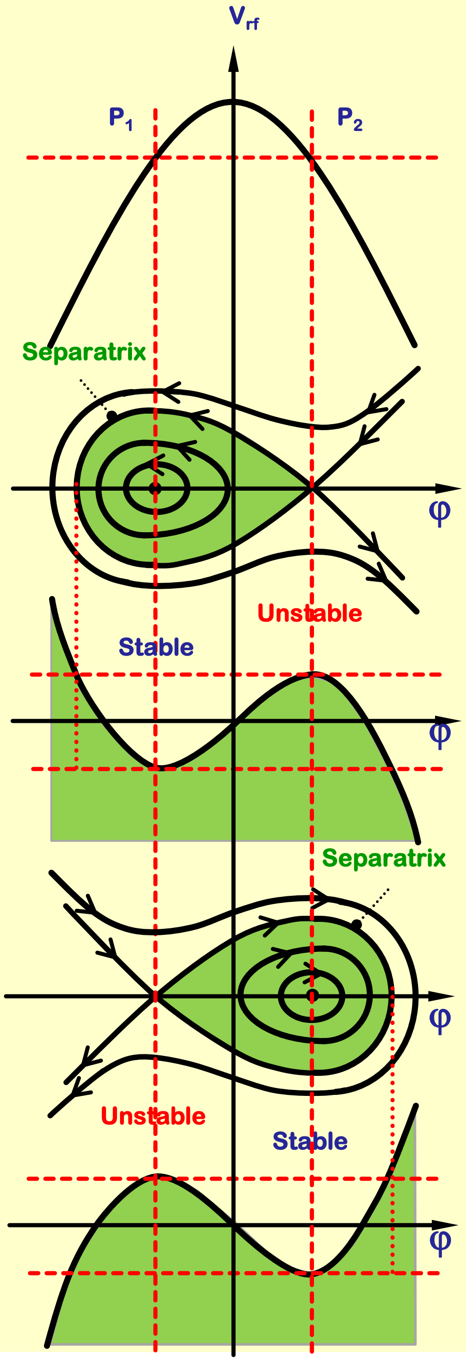
How can we further reduce possible beam losses during passing through the transition energy?

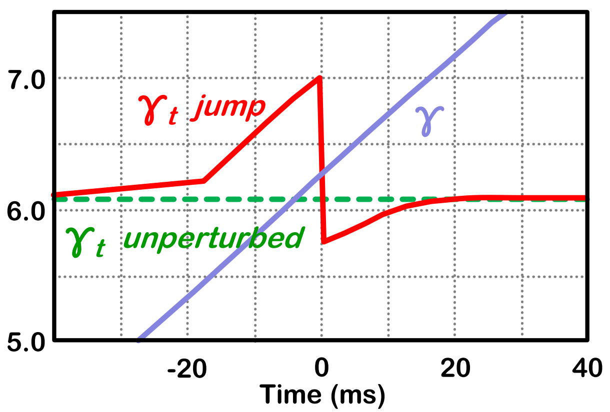
A hint

Use inventive principle “Skipping”

Conduct a process, or certain stages (e.g. destructible, harmful or hazardous operations) at high speed

Re-inventing synchrotron

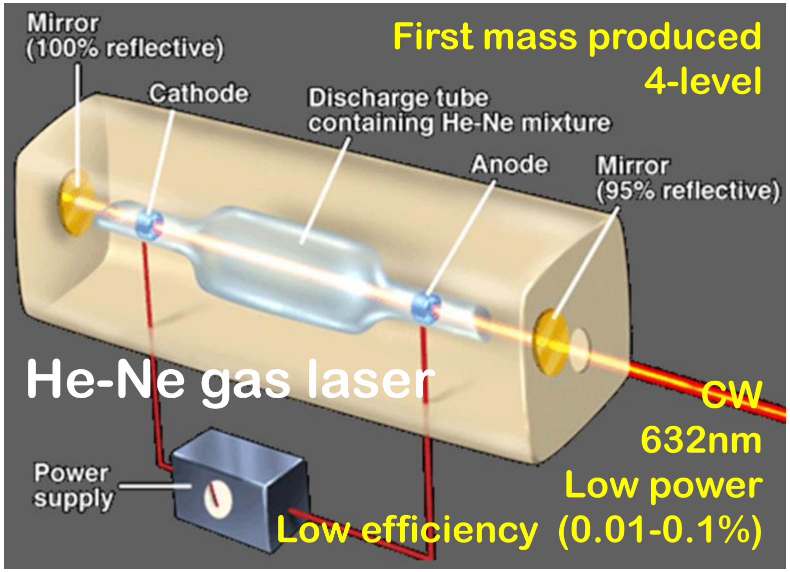


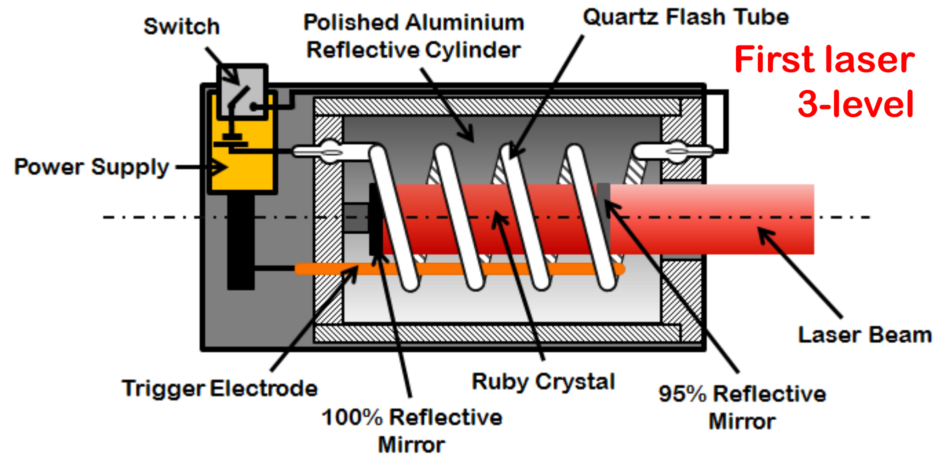


Crossing transition energy with γ_t jump technique

One can dynamically change optical lattice to modify behaviour of momentum compaction, so that crossing the transition occur with much higher derivative, and reduce the time duration of harmful impact – *"skipping"*

Examples of laser types

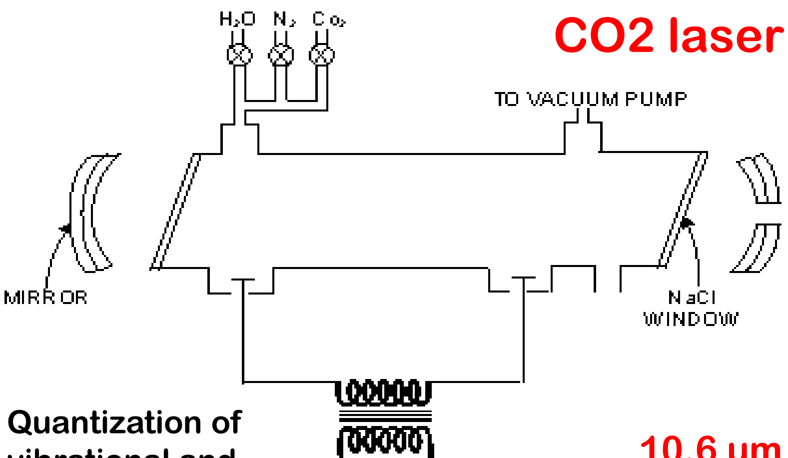




First laser
3-level

Ruby laser
694nm

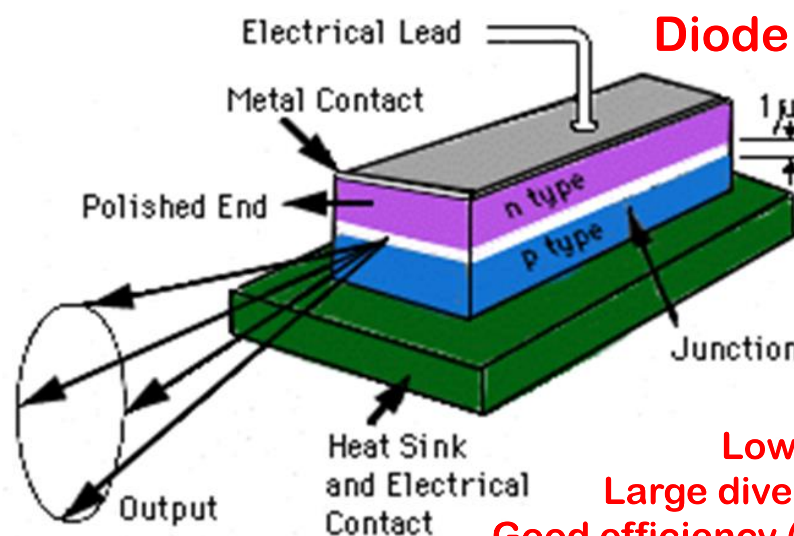
CO2 laser



Quantization of vibrational and rotational states of CO2 molecule

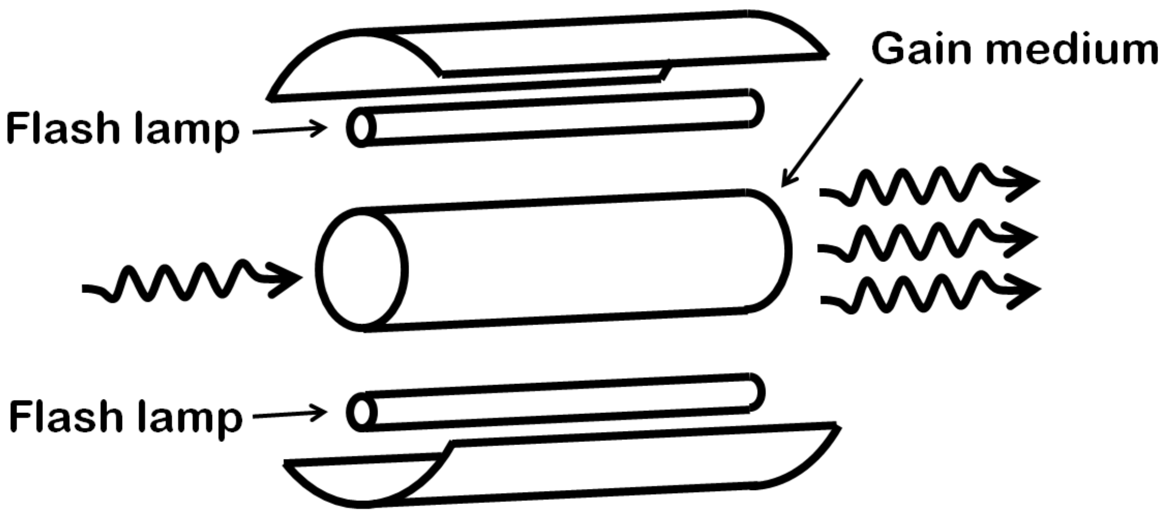
10.6 um
High power, kW in CW
Good efficiency (~ 30%)

Diode laser



Low power
Large divergence
Good efficiency (~ 40%)

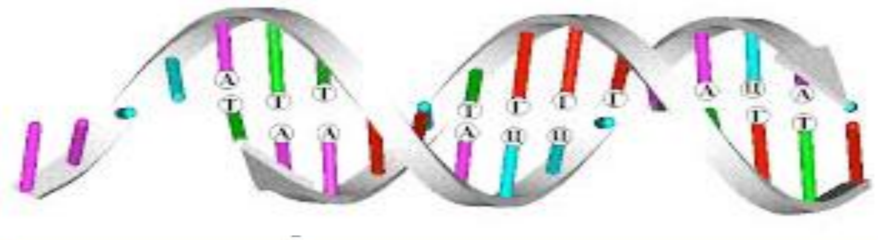
Laser amplifiers

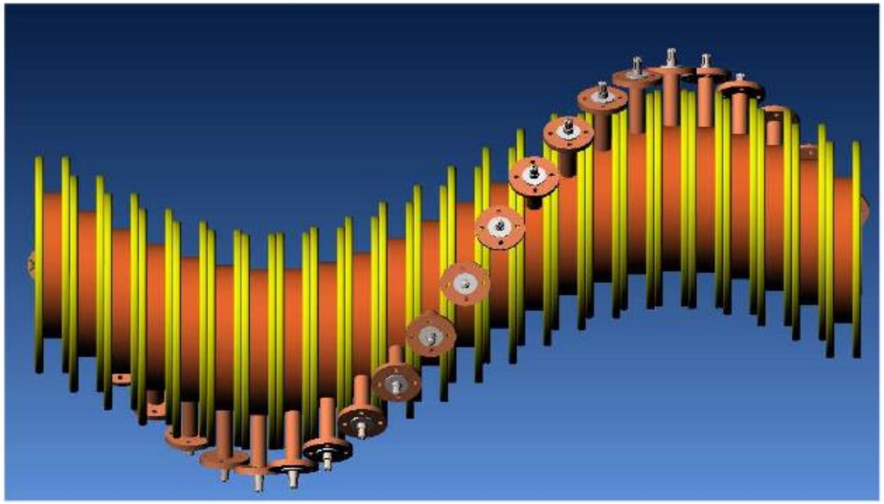


Common principle: gain medium is pumped to produce gain for light at the wavelength of a laser made with the same material as its gain medium

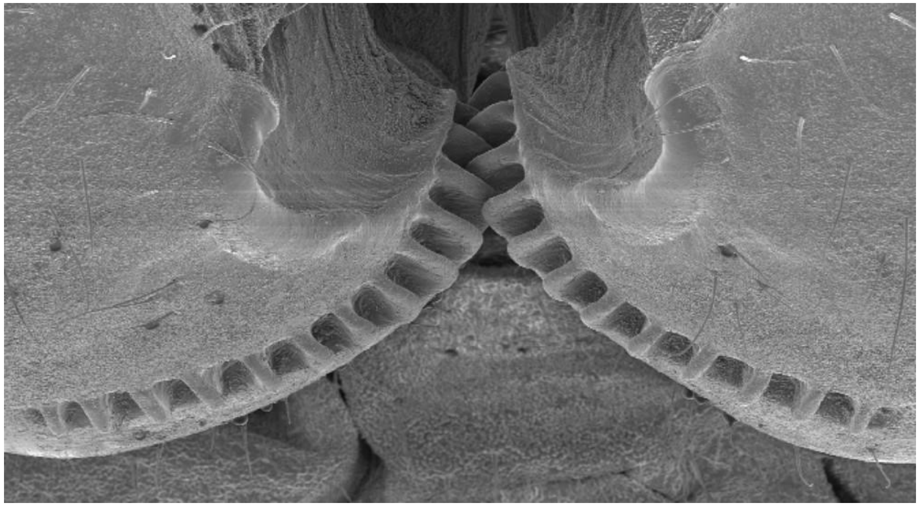
- **Ultra-short and ultra high power – challenges:**
  - **Ultra short – nonlinear effect in the medium**
  - **High power – heating the amplifier medium**
- **These challenges limit rep rate, power and efficiency**
  - **Some of the most powerful lasers fire just once per few hours!**
- **A lot of inventions in the field of light amplification**

Inventions inspired by nature

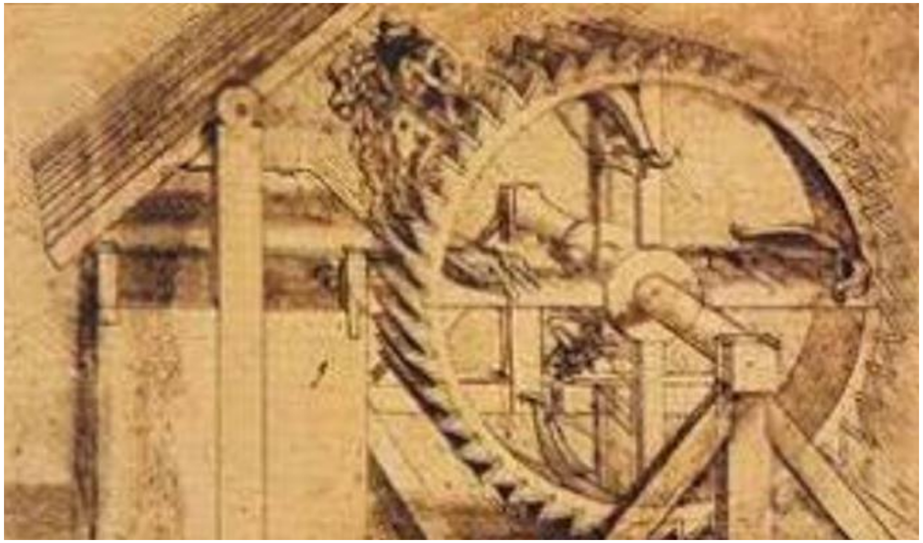




Muon Collider cooling channel and the shape of DNA

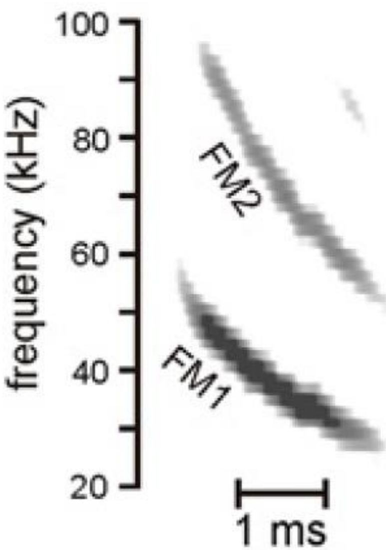


Insects used gears for millions of years

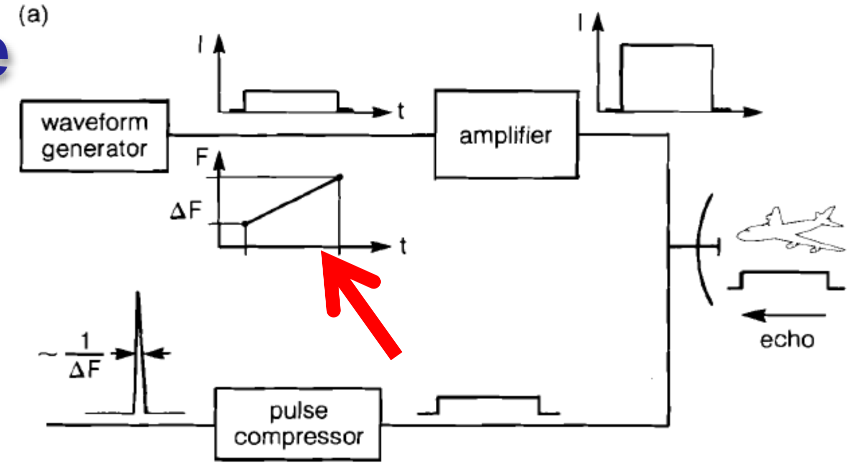


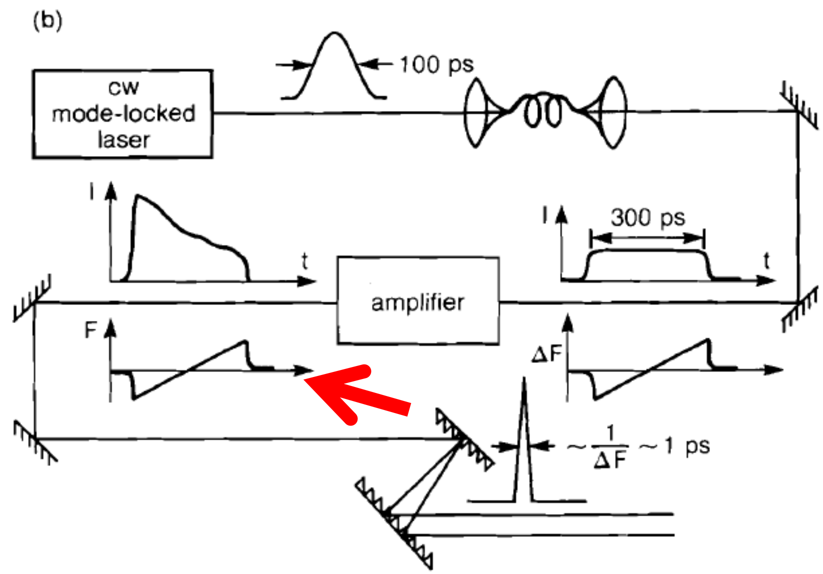
Inventions inspired by nature

Chirped pulses in radar or CPA and chirped sound in flying bats



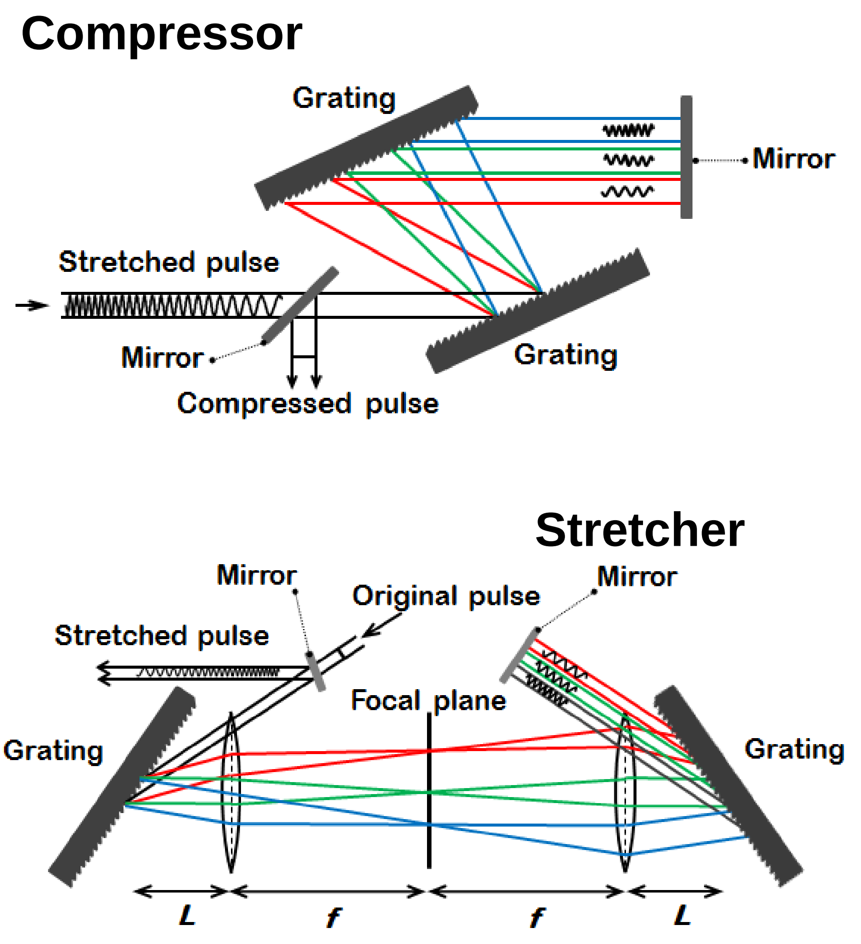
"The biologically inspired method adopts the bat's frequency-hopping technique to suppress pulse-echo ambiguity in wideband systems, a serious problem for man-made wideband radar and sonar systems"



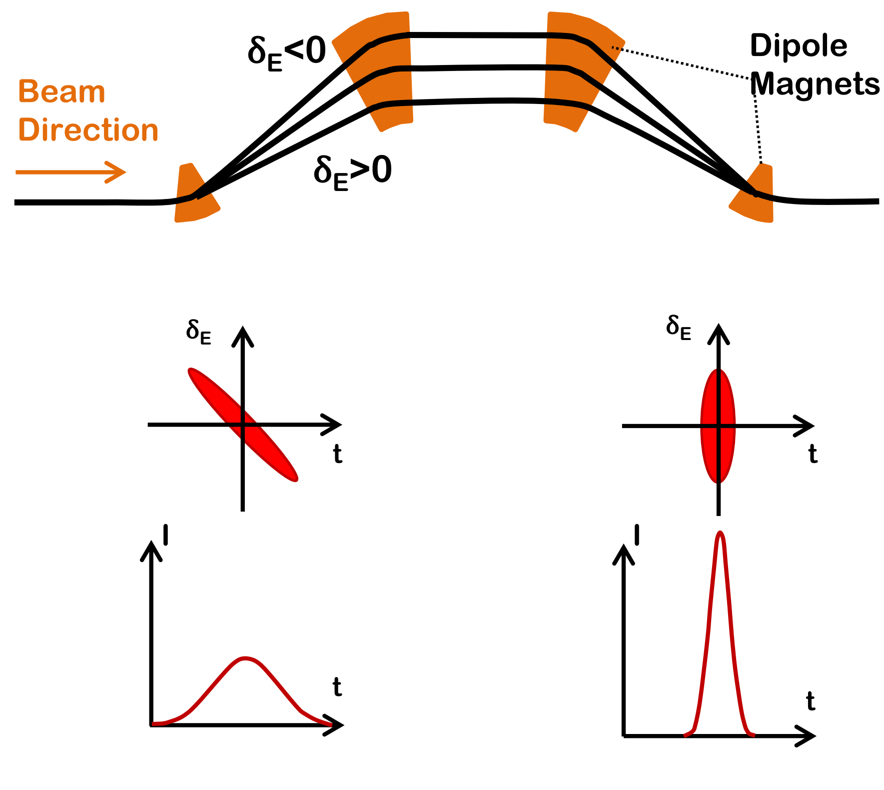


"How frequency hopping suppresses pulse-echo ambiguity in bat biosonar"
Chen Ming et al., https://doi.org/10.1073/pnas.2001105117

Beam and laser bunch/pulse compression



Laser

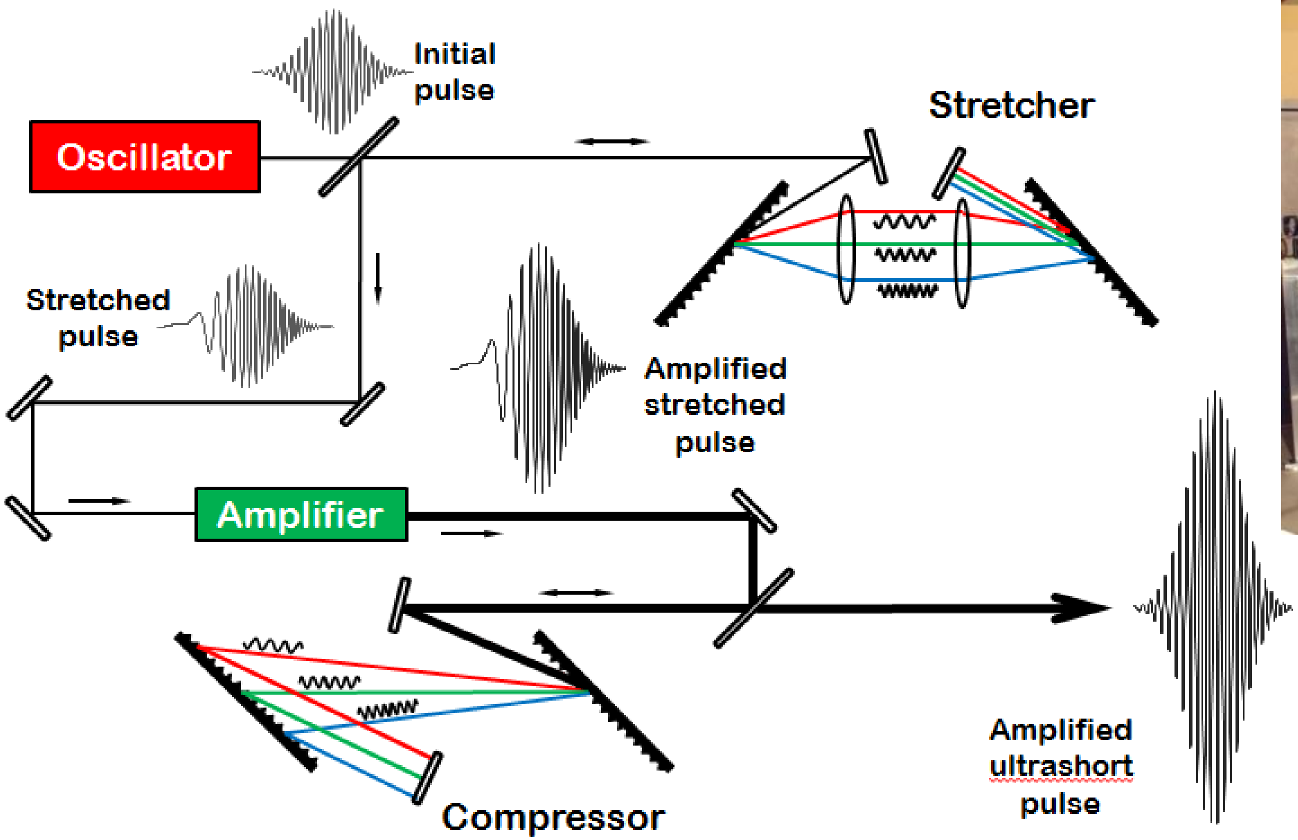


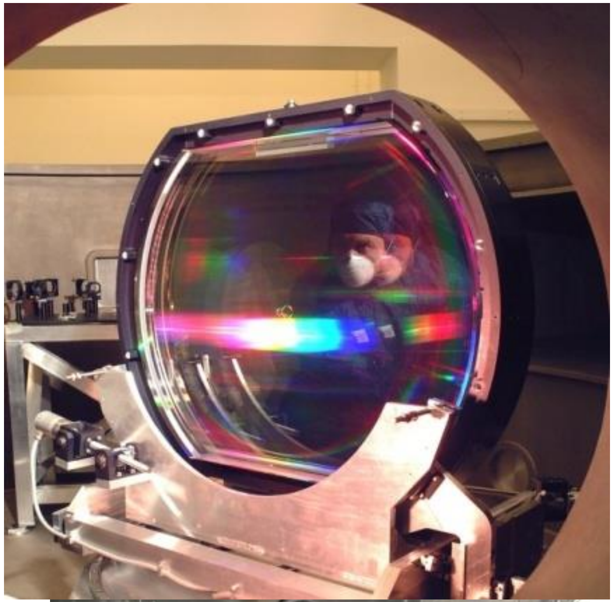
Beam

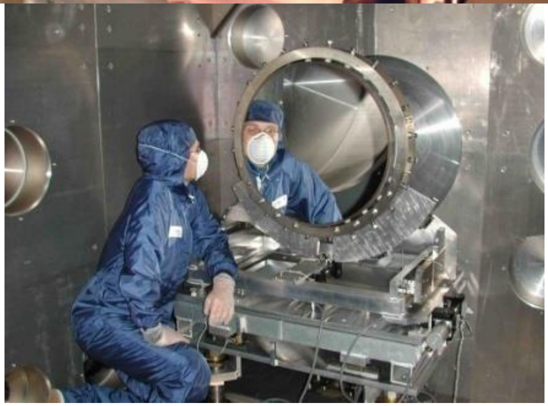
Both in laser and beam use z-Energy correlation to compress/stretch the pulse – one more general inventive principle

Telescope is needed inside stretcher to create "negative distance"

CPA – Chirped Pulse Amplification

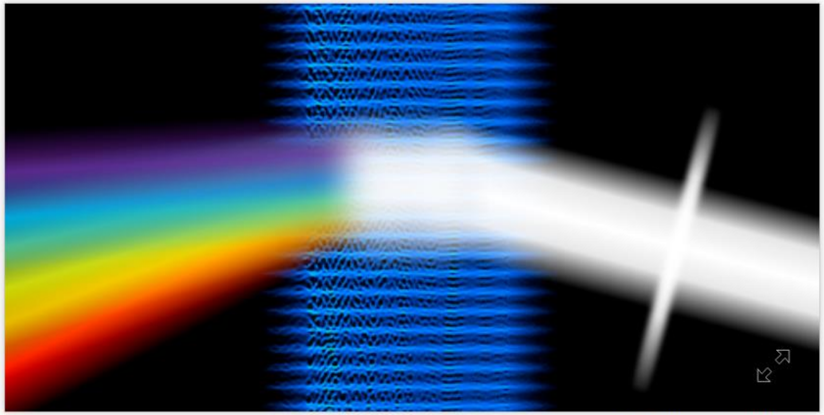






- Re-inventing CPA: what if power increase so much further that gratings will not survive even the stretched pulse?
- Hint: if you cannot avoid damaging material, try to use material that is already damaged, or use principle of short-lived objects

Re-inventing CPA



M. Edwards/Stanford University

- Compact high-power laser system may benefit* from use of plasma transmission gratings for chirped pulse amplification
- Simulations suggest that the meter-scale final grating for a 10-PW laser could be replaced with a 1.5-mm-diameter plasma grating, allowing compression to, for example, 22 fs with 90% efficiency and providing a path towards compact multipetawatt laser systems

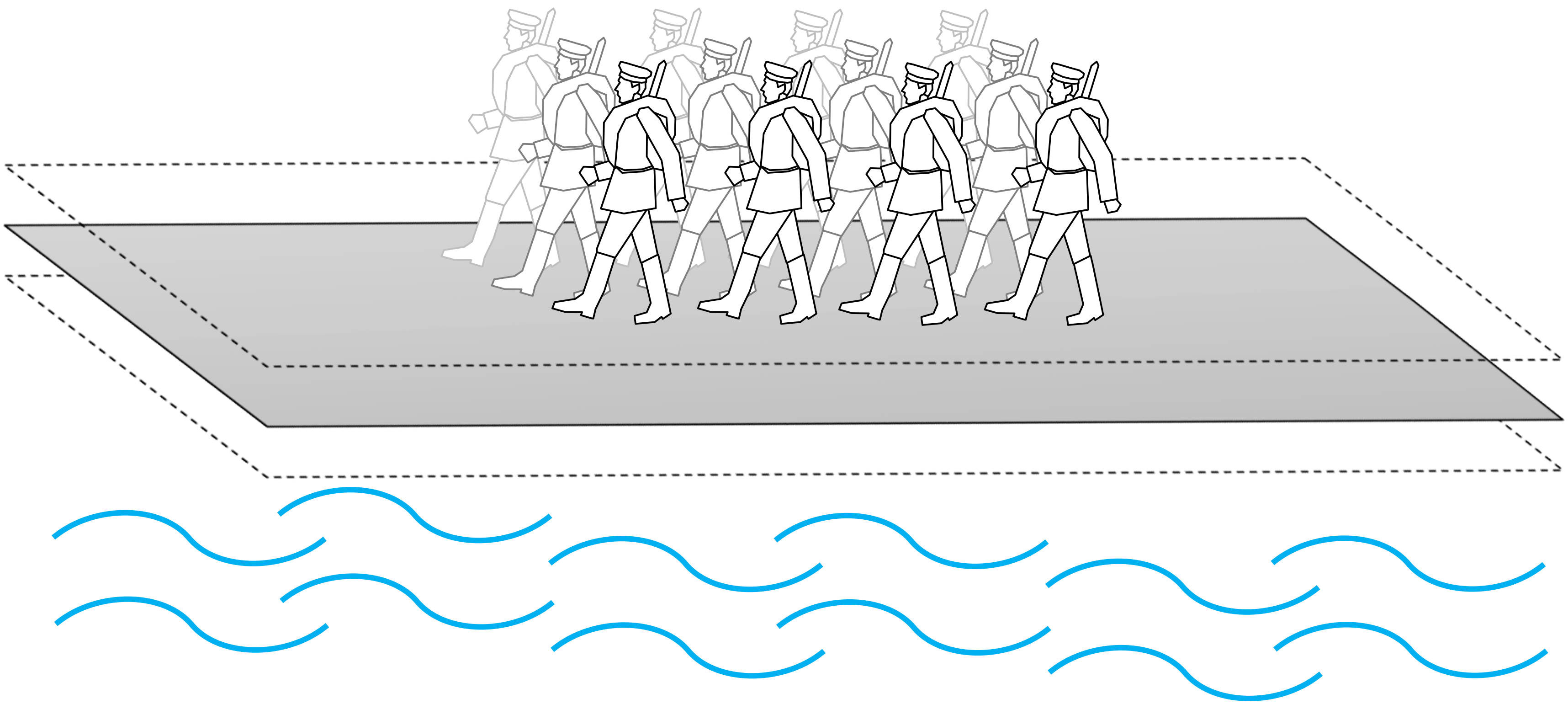
* M. R. Edwards and P. Michel, "Plasma transmission gratings for compression of high-intensity laser pulses," Phys. Rev. Applied 18, 024026 (2022) https://journals.aps.org/prapplied/abstract/10.1103/PhysRevApplied.18.024026

Plasma Gratings for High-Power Lasers, August 9, 2022• Physics 15, s108 https://physics.aps.org/articles/v15/s108

Resonances, bridges & accelerators

Collapse of the “Egyptian bridge” in Saint-Petersburg in 1905, when the squadron of the life guards regiment was passing through the bridge, is usually explained by resonance

Resonances, bridges & accelerators



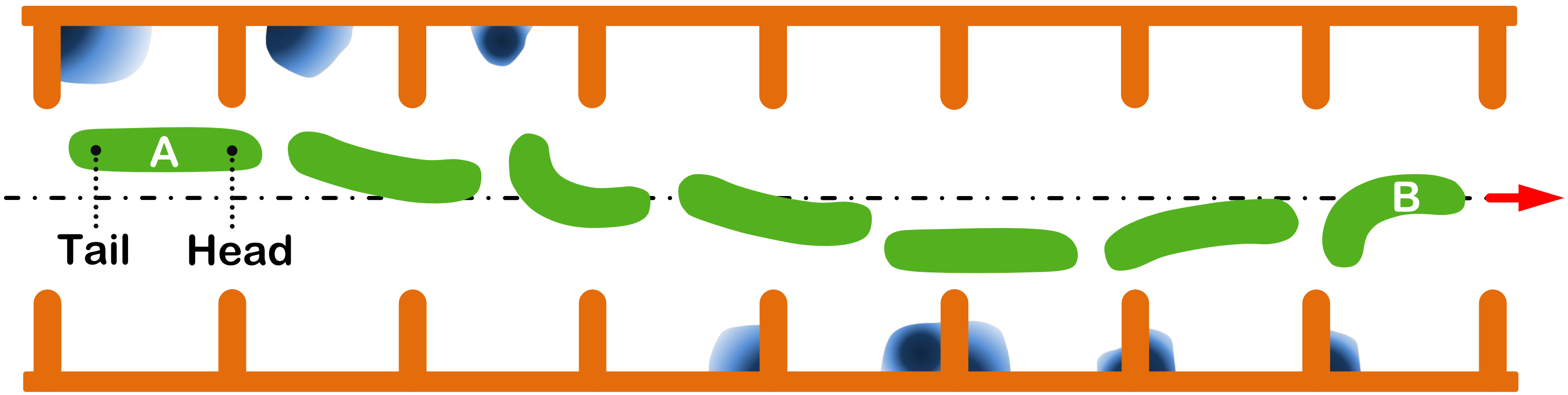
Resonances, bridges & accelerators

Collapse of the “Egyptian bridge” in Saint-Petersburg in 1905, when the squadron of the life guards regiment was passing through the bridge, is usually explained by resonance

It is not clear if this explanation is correct (most of regiment was on horses) but we know for sure that damaging resonance phenomena do happen, and in accelerators too

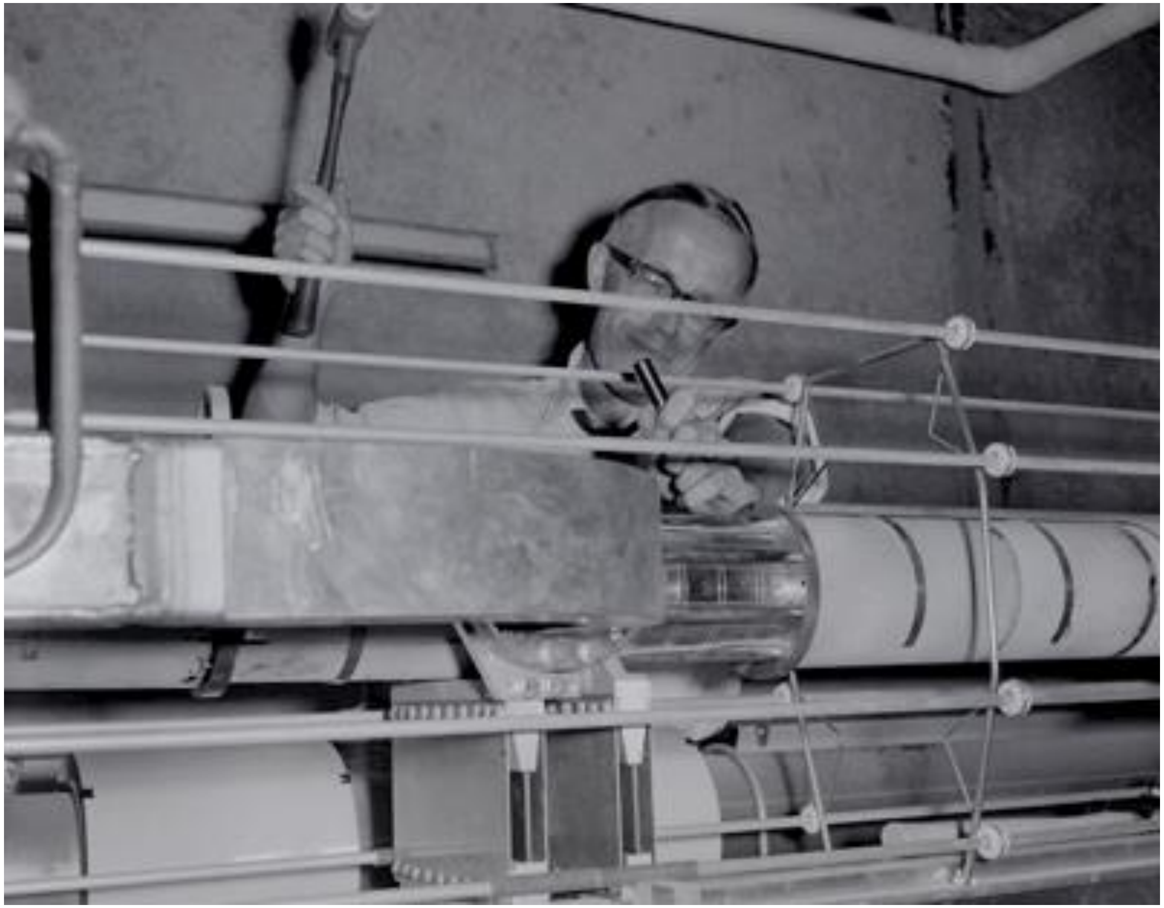
Wakefiels – fields left by bunch in accelerating structure

In RF cavity these fields can build up resonantly and disrupt the bunch itself in the so called Beam Break Up (BBU) instability



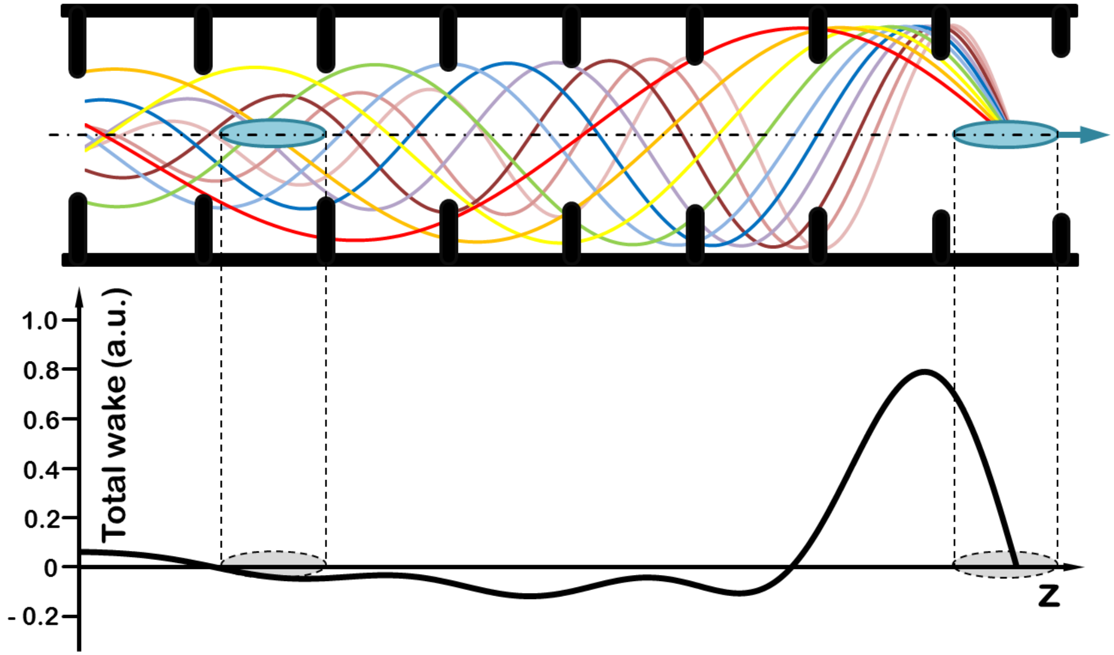
The problem was that all accelerating structures of 2 mile SLAC linac were exactly the same!
Resonance build up of the effect on the bunch
Observed multi-bunch multi-section
Beam Break Up instability

Wakefields and how to cure them with a hammer



To take care of BBU, it was necessary to "detune" the individual cells of the accelerator to prevent coherent build up of the wakefield forces. The detuning process was accomplished in the SLAC linac by dimpling the radial dimensions of each cell so that the frequencies of the lowest dipole components of the wakefields vary slightly from cell to cell. This "delicate" correction was applied to the as-build accelerator with handheld hammers

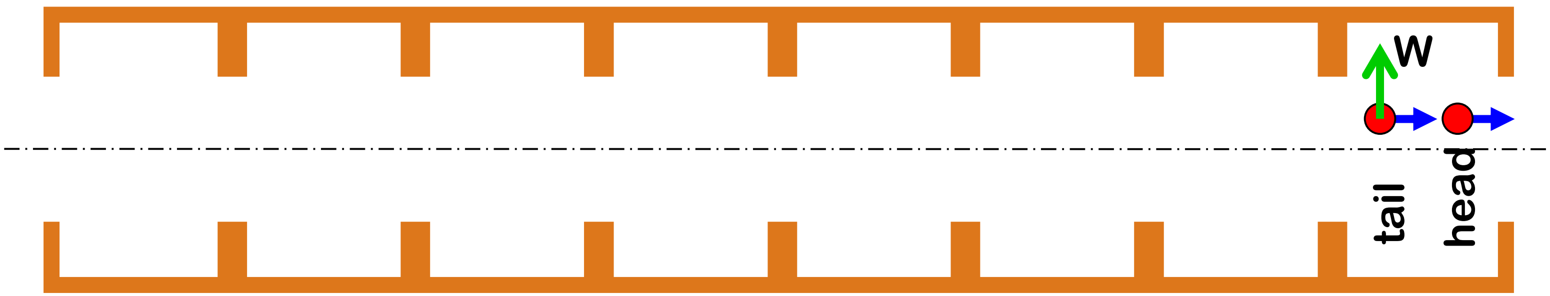
Linac: transverse wakefields



- Bunches induce field in the cavities
- Later bunches are perturbed by these fields
- Bunches passing off-centre excite transverse higher order modes (HOM)
- Fields can build up resonantly
- Later bunches are kicked transversely
- => multi- and single-bunch beam break-up (MBBU, SBBU)
- Emittance growth!!!

Re-invent the way to cure Beam Break Up

Assume the bunch is off-center in accelerating cavity and the bunch head excites transverse dipole wakefield W that gives additional defocusing force for the tail of the same bunch which can result in emittance growth and BBU



Can you suggest a way to fix this problem?

Hint: use resources that you already have in the system

Re-invent the way to cure Beam Break Up

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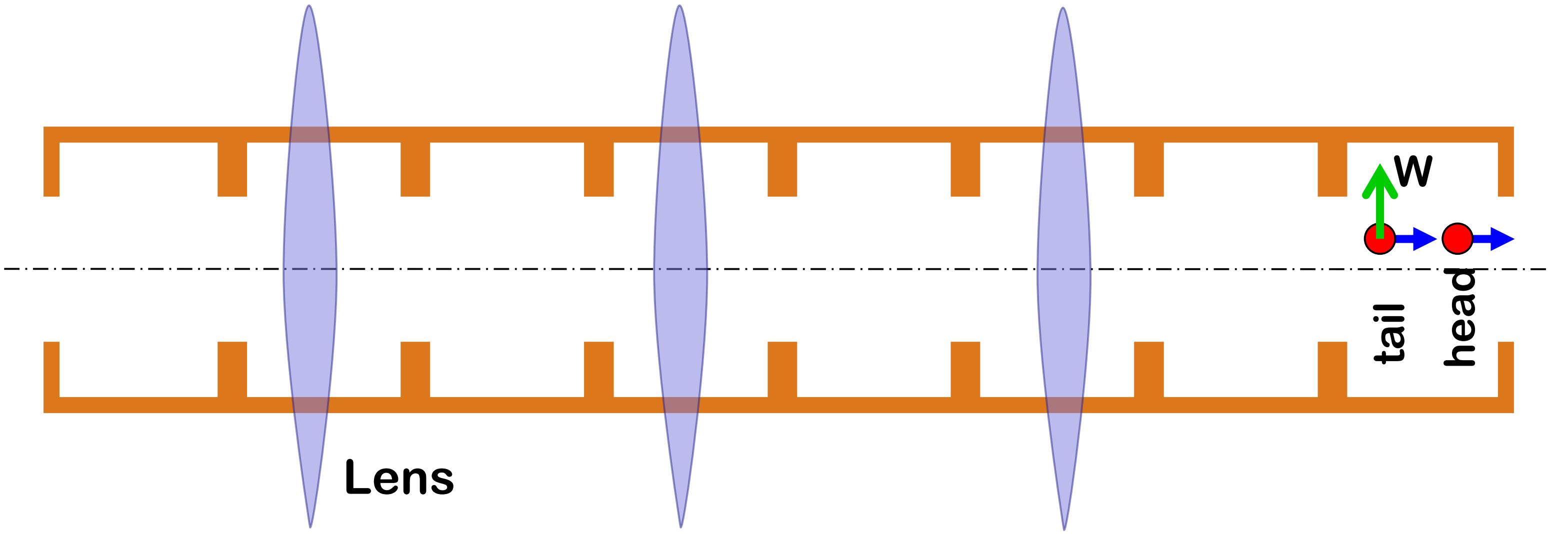

Can you suggest a way to fix this problem?

Hint: use resources that you already have in the system

Hint 2: what resources do we have? E.g. focusing quadrupoles distributed along the linac

Re-invent the way to cure Beam Break Up

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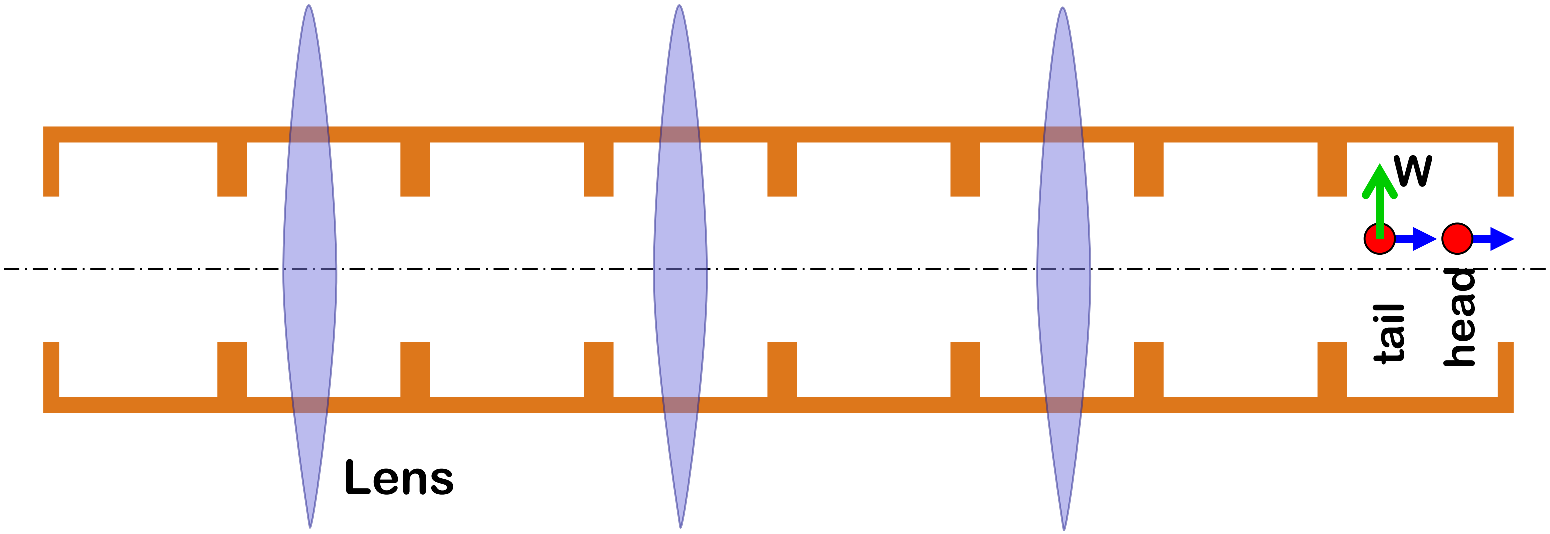
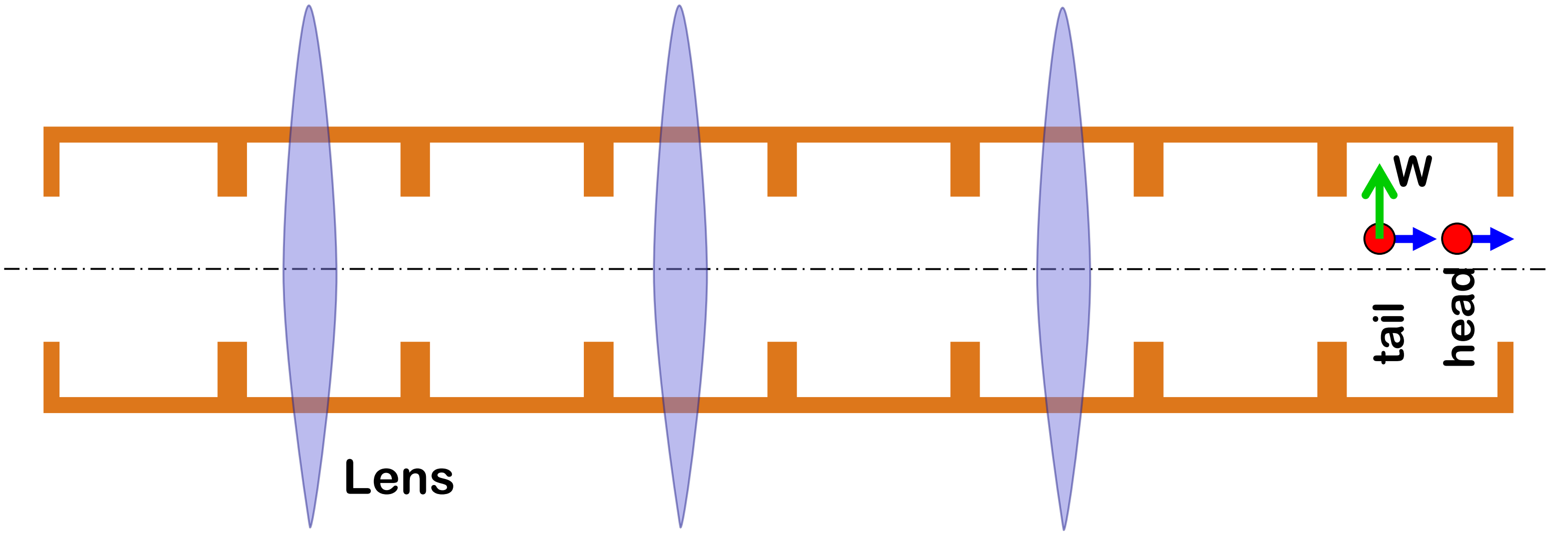


Can you suggest a way to fix this problem?
Hint: use resources that you already have in the system
Hint 2: what resources do we have? E.g. focusing quadrupoles distributed along the linac
Hint 3: The wake results in different focusing for the head and tail of the bunch. How can you add additional focusing that will compensate this difference?

Re-invent the way to cure Beam Break Up

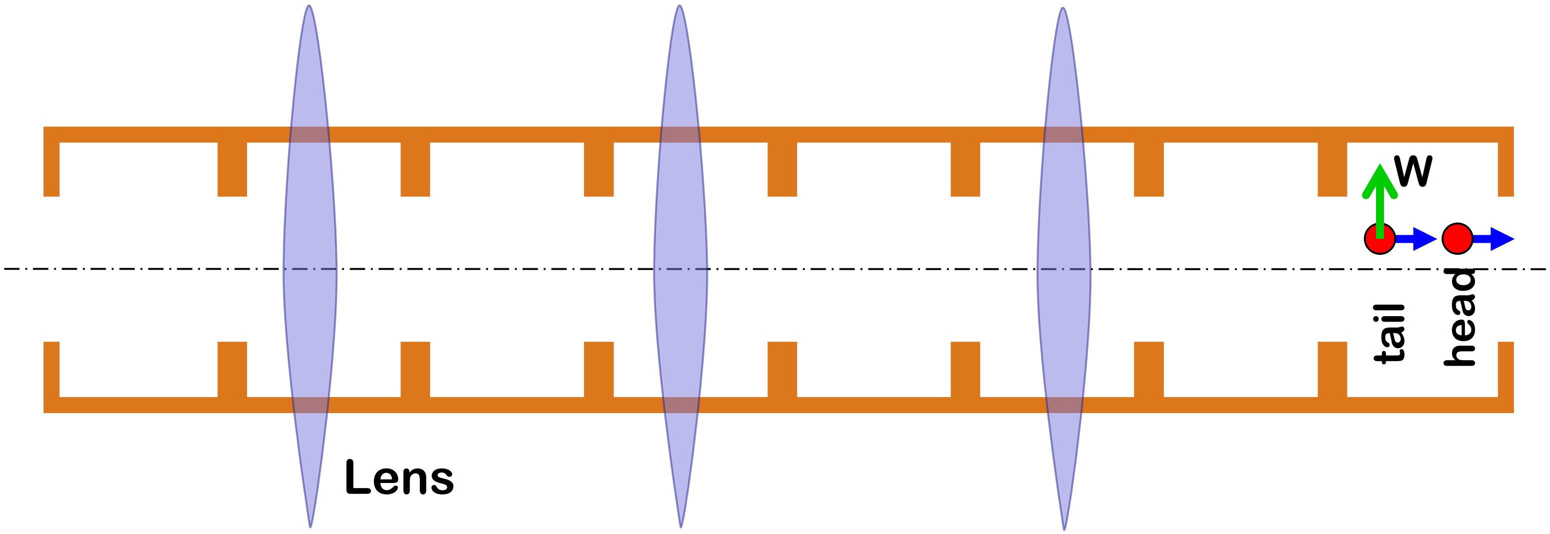
Assume the bunch is off-center in accelerating cavity and the bunch head excites transverse dipole wakefield W that gives additional defocusing force for the tail of the same bunch which can result in emittance growth and BBU



Can you suggest a way to fix this problem?
Hint: use resources that you already have in the system
Hint 2: what resources do we have? E.g. focusing quadrupoles distributed along the linac
Hint 3: The wake results in different focusing for the head and tail of the bunch. How can you add additional focusing that will compensate this difference?
Hint 4: Recall how CPA or bunch compression is created?

Beam Break Up and its cure - BNS

Assume the bunch is off-center in accelerating cavity and the bunch head excites transverse dipole wakefield W that gives additional defocusing force for the tail of the same bunch which can result in emittance growth and BBU

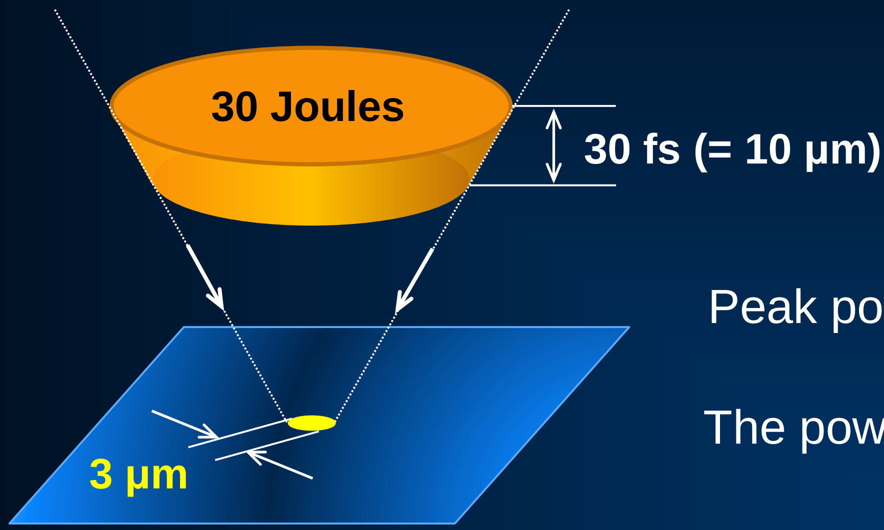


BNS damping – the wake W acting on the tail is additional defocusing – to compensate it one need to decrease energy of the tail in such a way that effectively increasing focusing by lenses in the accelerator channel will exactly cancel the defocusing effect of the wakes

So, the BNS damping achieved by placing bunch off-crest of RF pulse, which creates corresponding and optimal BNS energy spread over the bunch (E-z correlation, or chirp, like in CPA or in travelling focus)

Contemporary high-power lasers

... are impressive



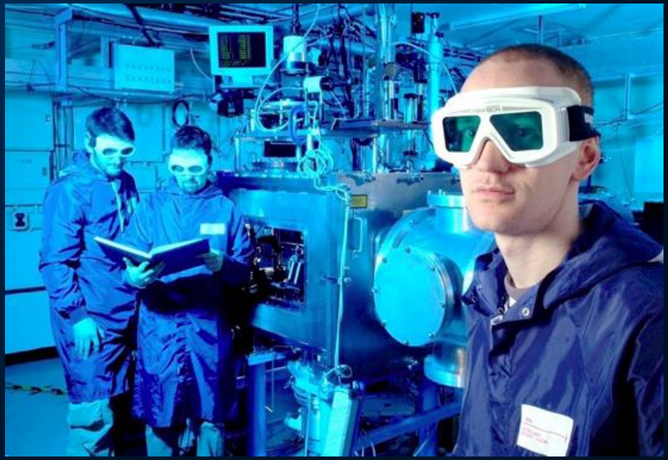
Peak power 10^{15} W

The power density at the focus is 10^{22} W/cm^2

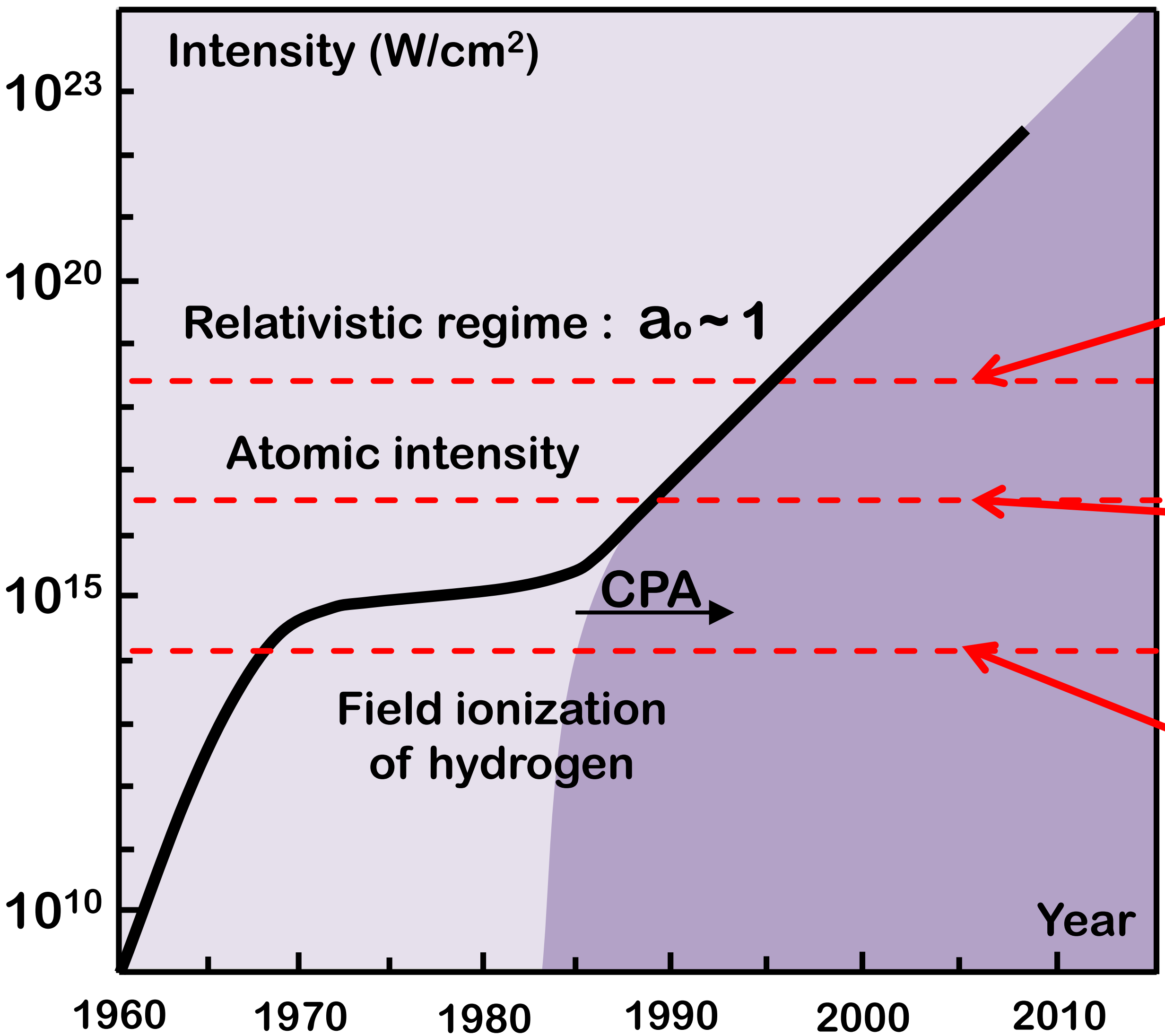
Laser of this power instantly ionizes any substance

Electrons carried along by the field of such a laser instantly become relativistic...

…although conventional resonators usually used for such acceleration



Laser intensity



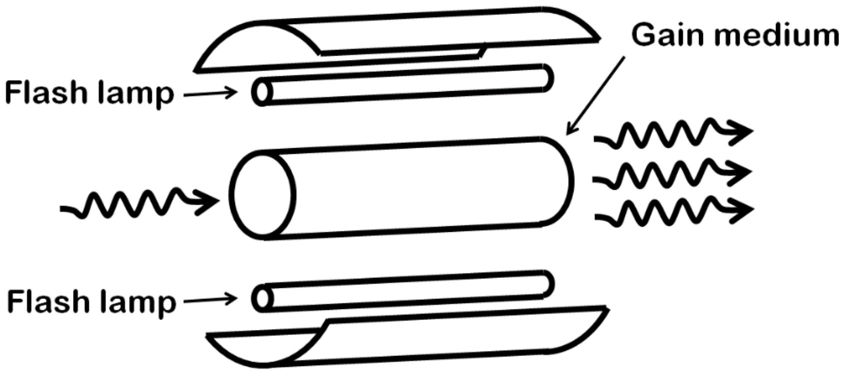
a_0 ~1 for red laser

$$I_a = \frac{\varepsilon_0 c E_a^2}{2} \cong 3.51\times10^{16}\,\frac{W}{cm^2}$$

$$I_c = \frac{I_a}{256} \approx 1.4\cdot10^{14}\,W/cm^2$$

Progress in peak intensity since laser invention in 1960

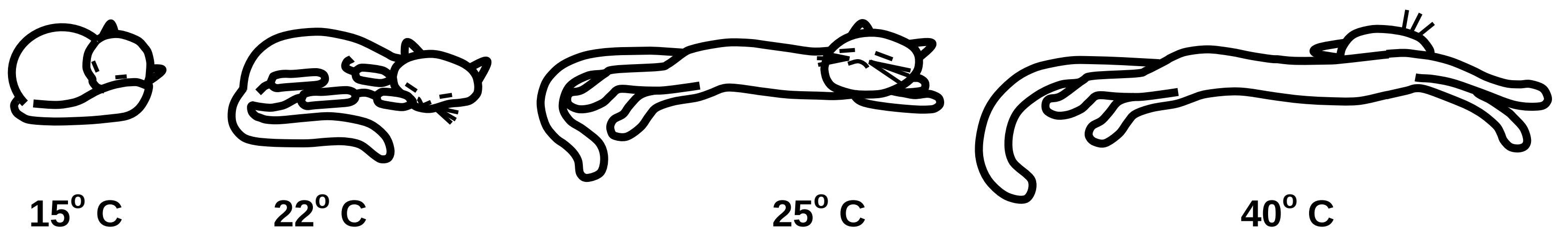
Laser amplifiers & inventions inspired by nature



Problem:
As intensity of the laser light increase, it takes much more time for the media to cool down and be ready for next use

Contradiction:
To be improved: INTENSITY,
What gets worse: REP RATE

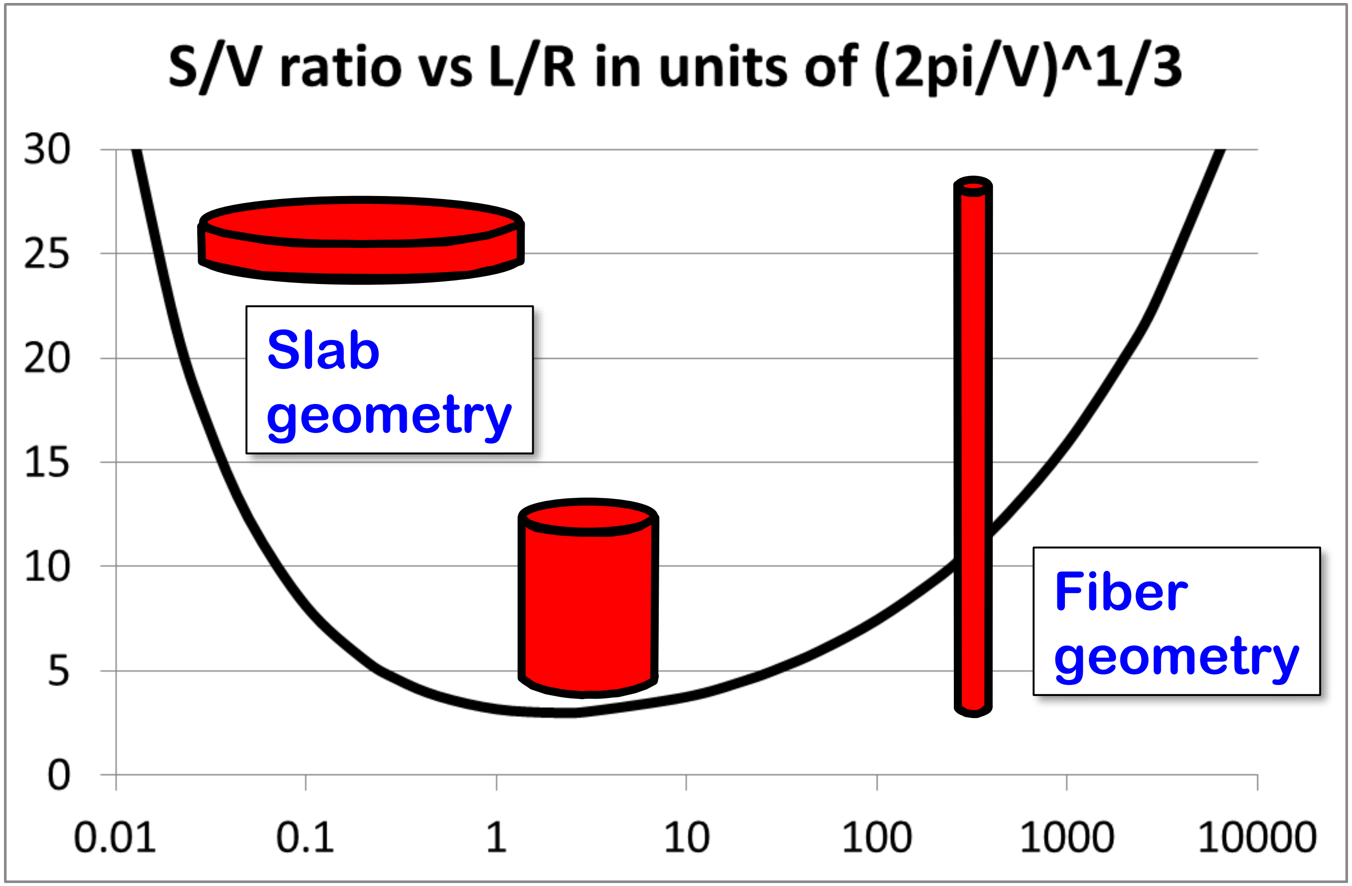
- **A general principle which can solve this can be taken from nature:**
  - **4: Volume to surface ratio – change it to alter the characteristics such as <u>cooling rate</u>, fields of the object, etc**



The cat clearly knows the principle of surface to volume ratio

- **Fiber lasers and Dipole laser technology illustrate this principle**

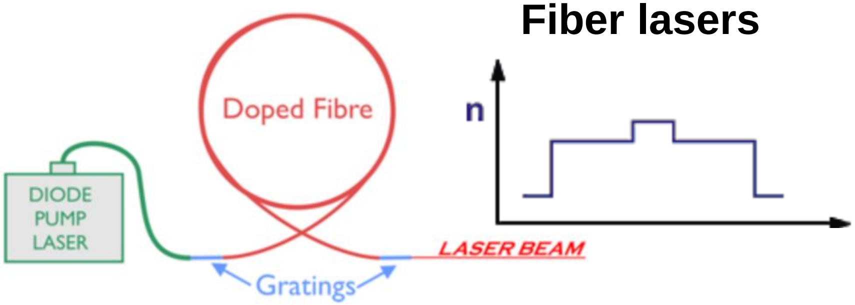
Fiber lasers and slab lasers



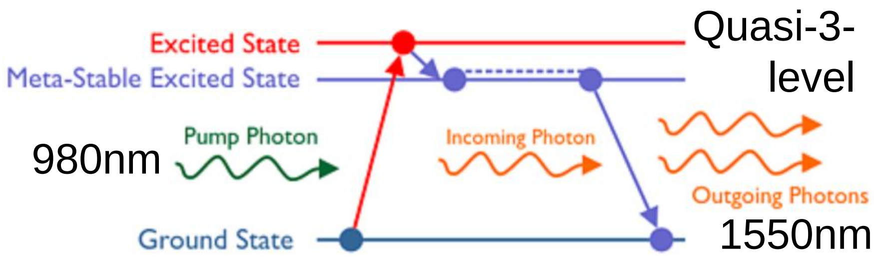
- **Fiber lasers and DiPOLE laser technology use the principle of larger surface to volume ratio**
  - **Possibility of high power, high rep rate, high efficiency**

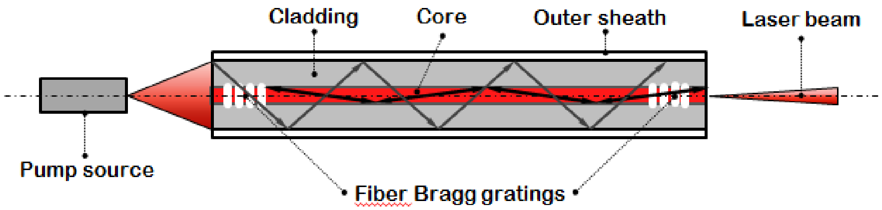
Fiber laser and DiPOLE lasers

Fiber lasers



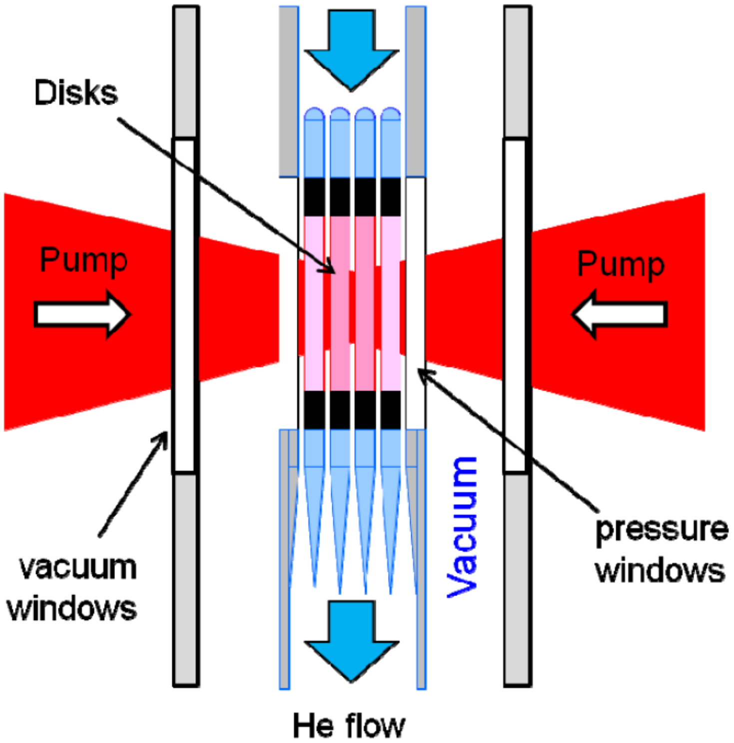
Diode pumped, Erbium-doped gain media



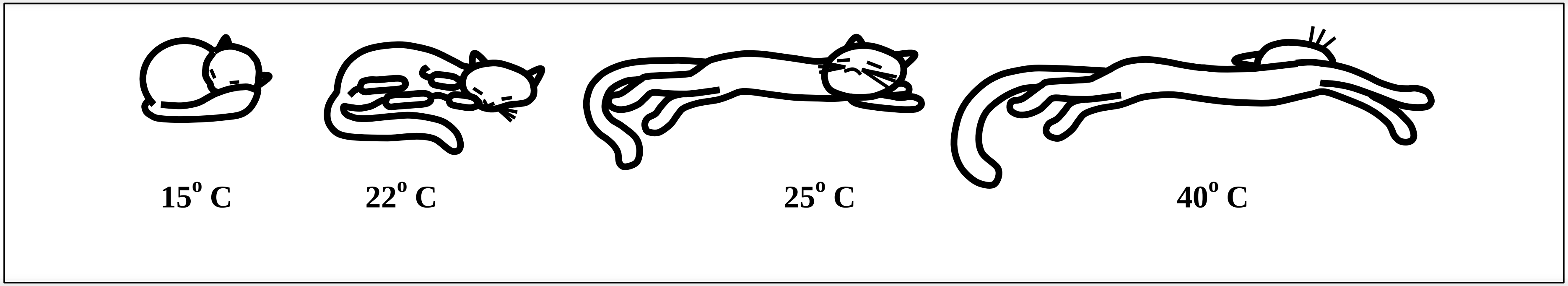


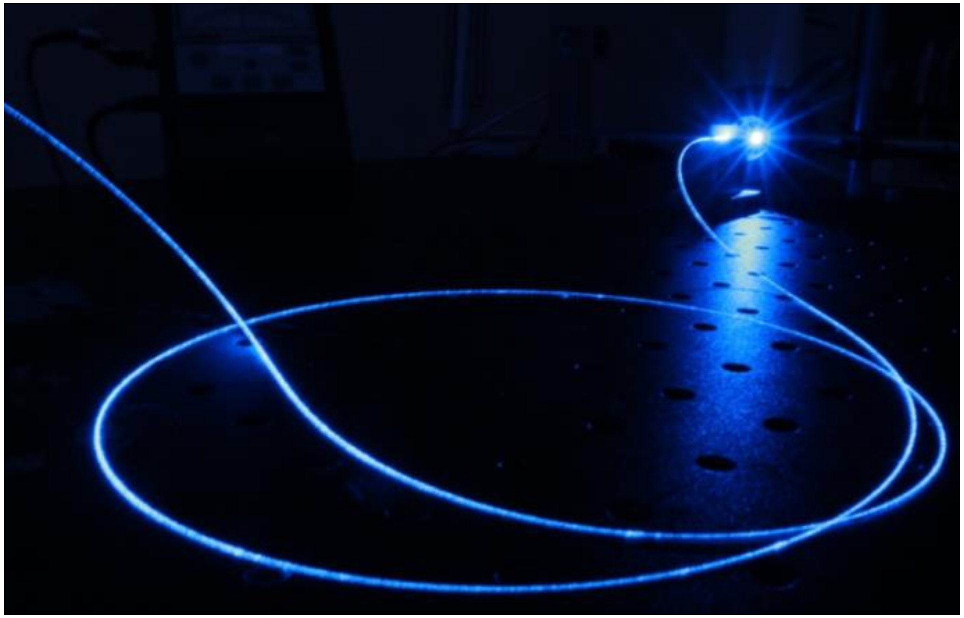
Bragg Gratings create reflections, acting as mirror
High efficiency, CW or sub-ps pulses
In CW mode – tens of kW
In pulsed mode – mJ in tens of kHz

DiPOLE = Diode Pumped Optical Laser Experiment – developed by CLF/RAL, UK

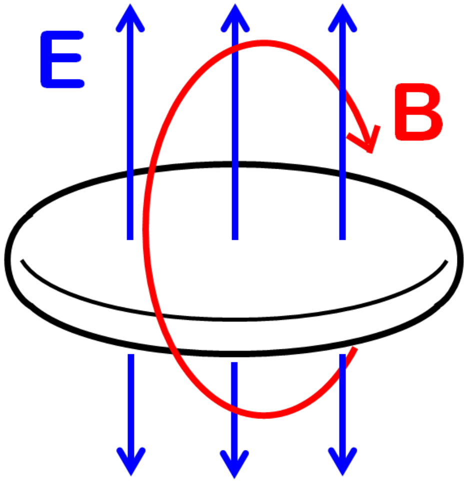


Cooled by cold He gas at 175K
Disks = Yb:YAG slabs
Aim to deliver kJ pulses at 10Hz
Pump at 939nm, radiate at 1030nm





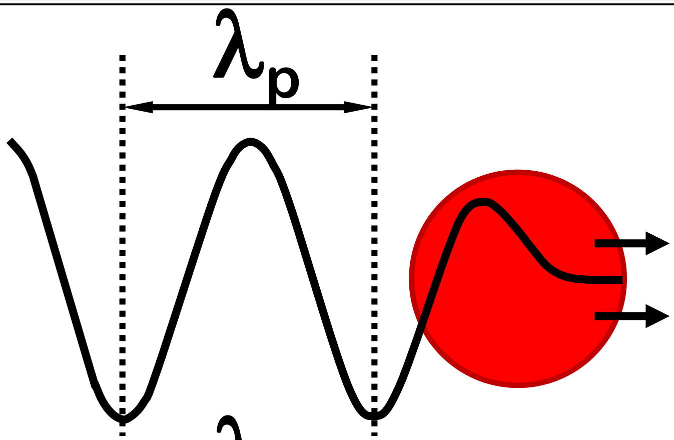
It seems there is a general inventive principle that connects cats and fiber lasers. And beams as well.



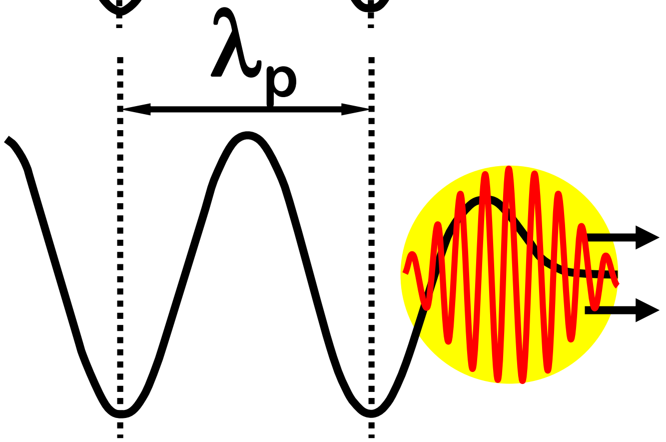
How to excite plasma

- **Availability of short sub-ps pulses of laser or beams stimulated rapid progress of plasma acceleration**

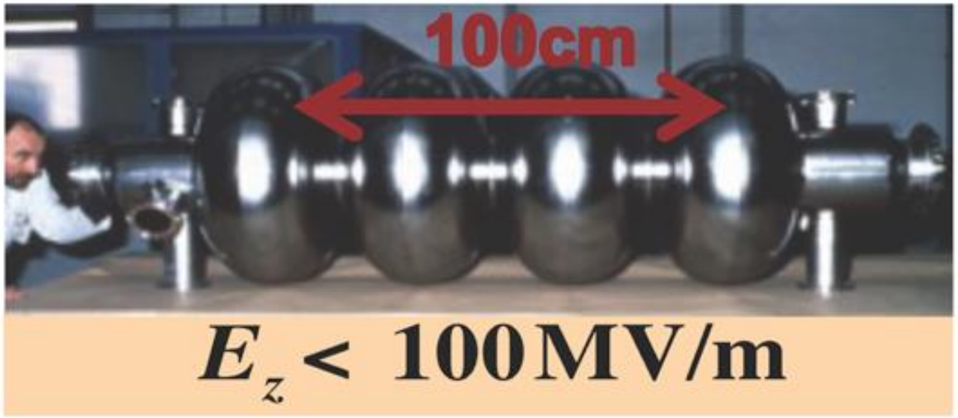
- **Plasma Wakefield Accelerator (PWFA)**
  - **A short high energy particle bunch**



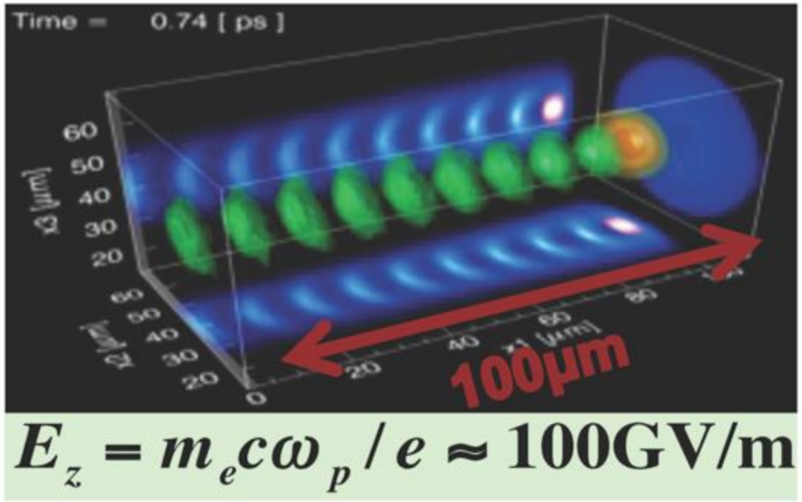
- **Laser Wakefield Accelerator (LWFA)**
  - **A short laser pulse of <u>high intensity</u>**



Lasers and particle acceleration



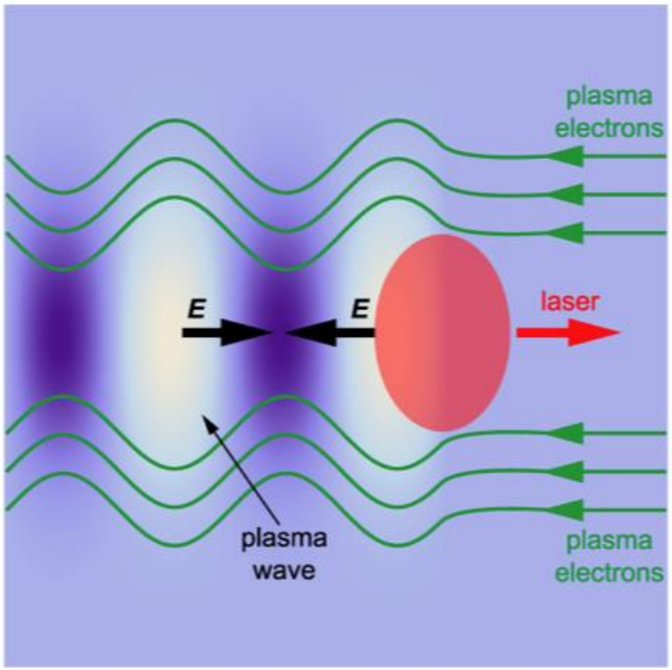
Accelerating structure, metal (normal conductive or super-conductive)

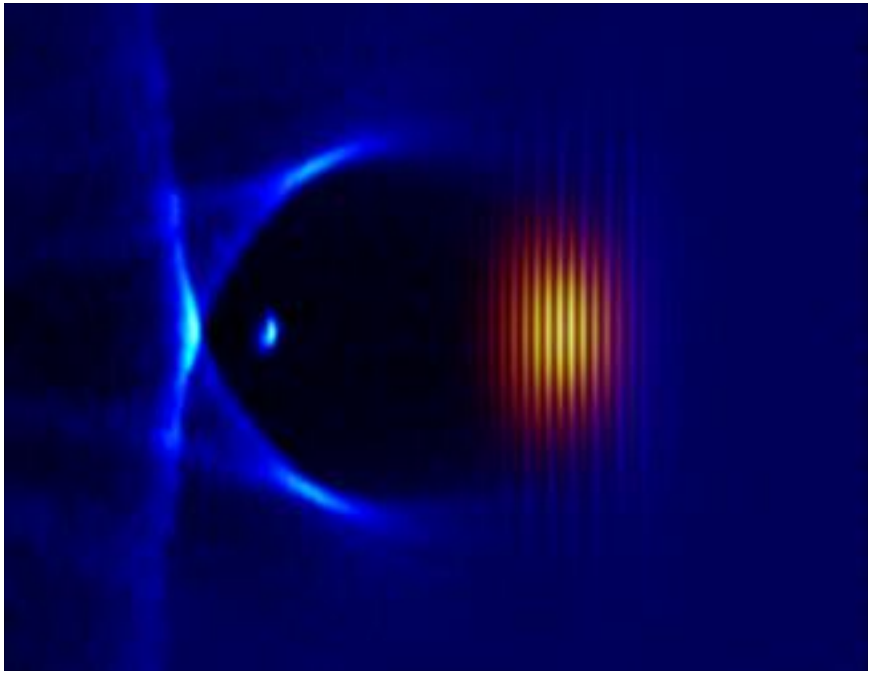


“Accelerating structure” produced on-the-fly in plasma by laser pulse

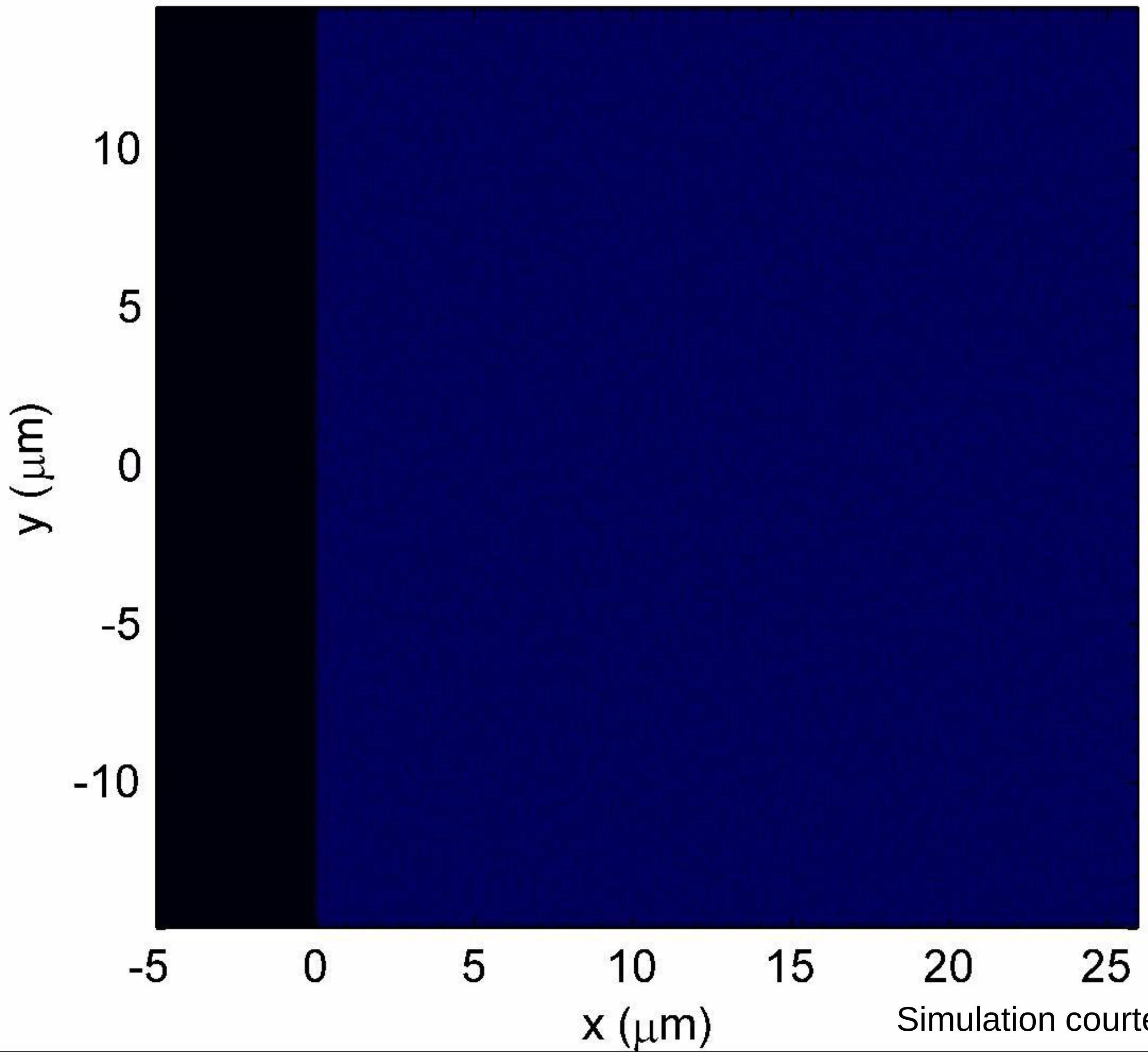
- **Let’s discuss couple of inventions related to laser plasma acceleration**

Laser-Driven Plasma Acceleration





- Ponderomotive force of short (50fs), intense (10^{18} W cm^{-2}) laser pulse expels plasma electrons while heavier ions stay at rest
- Electrons attracted back to ions, forming a bubble (blow-out regime) and setting up plasma wave which trails laser pulse
- Electric fields within plasma wave of order 100 GV/m formed



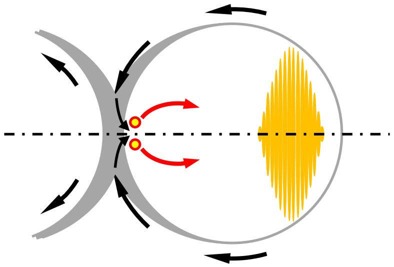
Simulation courtesy Prof Simon Hooker

How e- gets into the bubble – wave breaking

- **Wave breaking**
  - **Self-injection of background plasma electrons to the wake when some particles outrun the wake**

- **Other methods**
  - **External injection (difficult for so short bunches)**
  - **Can we re-invent other injection method?**

Re-inventing plasma acceleration



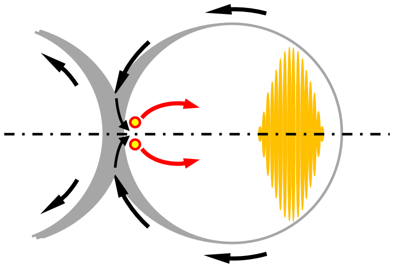
You saw from simulations and from this cartoon that some electrons are captured into the bubble and then accelerated

The number of these electrons that are captured is not large, and may be fluctuating

Can you suggest a way to significantly increase the number of captured and accelerated electrons?

Hint: Try to use parameter change principle

Re-inventing plasma acceleration



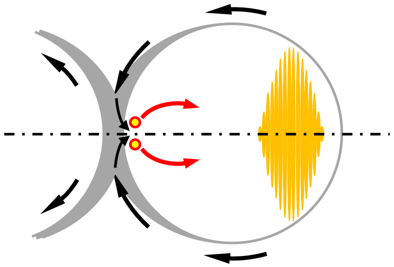
You saw from simulations and from this cartoon that some electrons are captured into the bubble and then accelerated

The number of these electrons that are captured is not large, and may be fluctuating

Can you suggest a way to significantly increase the number of captured and accelerated electrons?

Hint: Can you use something similar to gamma transition where you abruptly changed location of the accelerating basket?

Re-inventing plasma acceleration



You saw from simulations and from this cartoon that some electrons are captured into the bubble and then accelerated

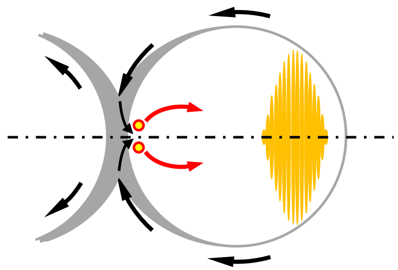
The number of these electrons that are captured is not large, and may be fluctuating

Can you suggest a way to significantly increase the number of captured and accelerated electrons?

Hint: what the size (length) of the bubble depend on?

$$\lambda_p = \frac{c}{f_p} \quad \rightarrow \quad \lambda_p \approx 0.1mm\sqrt{\frac{10^{17}cm^{-3}}{n}}$$

Re-inventing plasma acceleration



The size (length) of the bubble dependence:

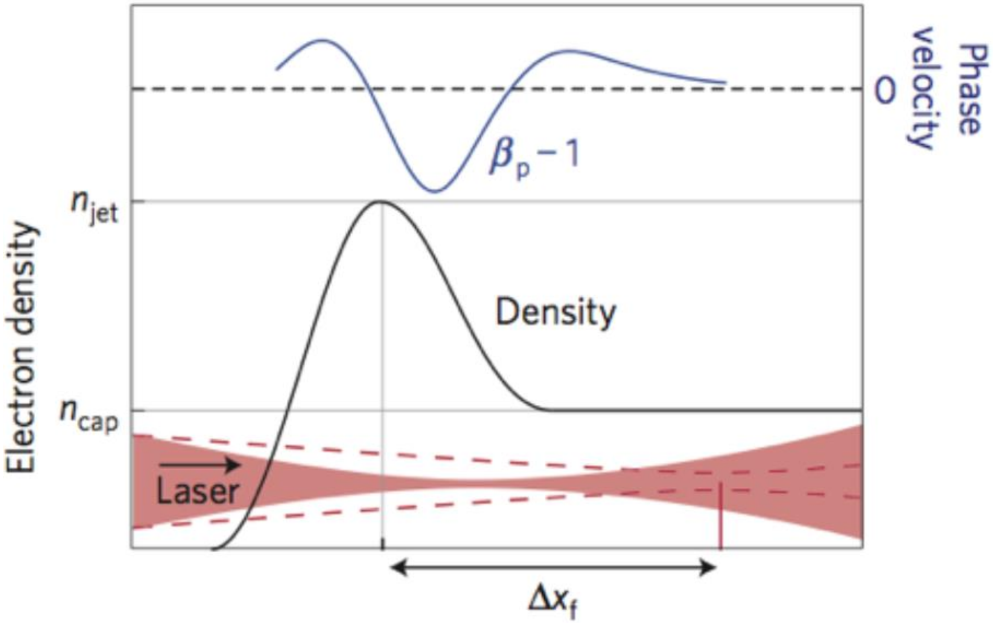
$$\lambda_p = \frac{c}{f_p} \quad \rightarrow \quad \lambda_p \approx 0.1mm\sqrt{\frac{10^{17}\, cm^{-3}}{n}}$$

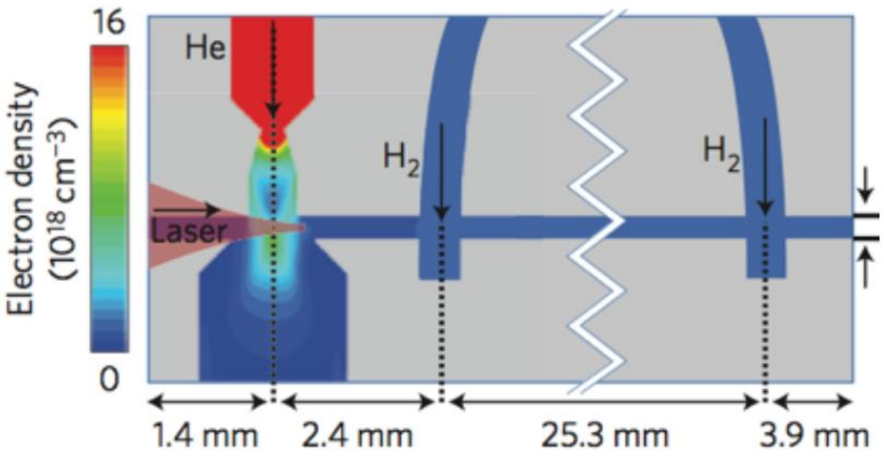
- We saw from simulations and from this cartoon that some electrons are captured into the bubble and then accelerated
- The number of these electrons that are captured is not large, and may be fluctuating
- There is a way to significantly increase the number of captured and accelerated electrons

Down-ramp injection: send laser to gas with decreasing density.
In this case the length of the bubble will constantly grow.
Electrons which were on the boundary of trapping area will now appear inside of plasma bubble => more electrons will be trapped and accelerated

H. Suk, et al., Phys. Rev. Lett. 86, 1011, 2001, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.86.1011

Down-ramp injection



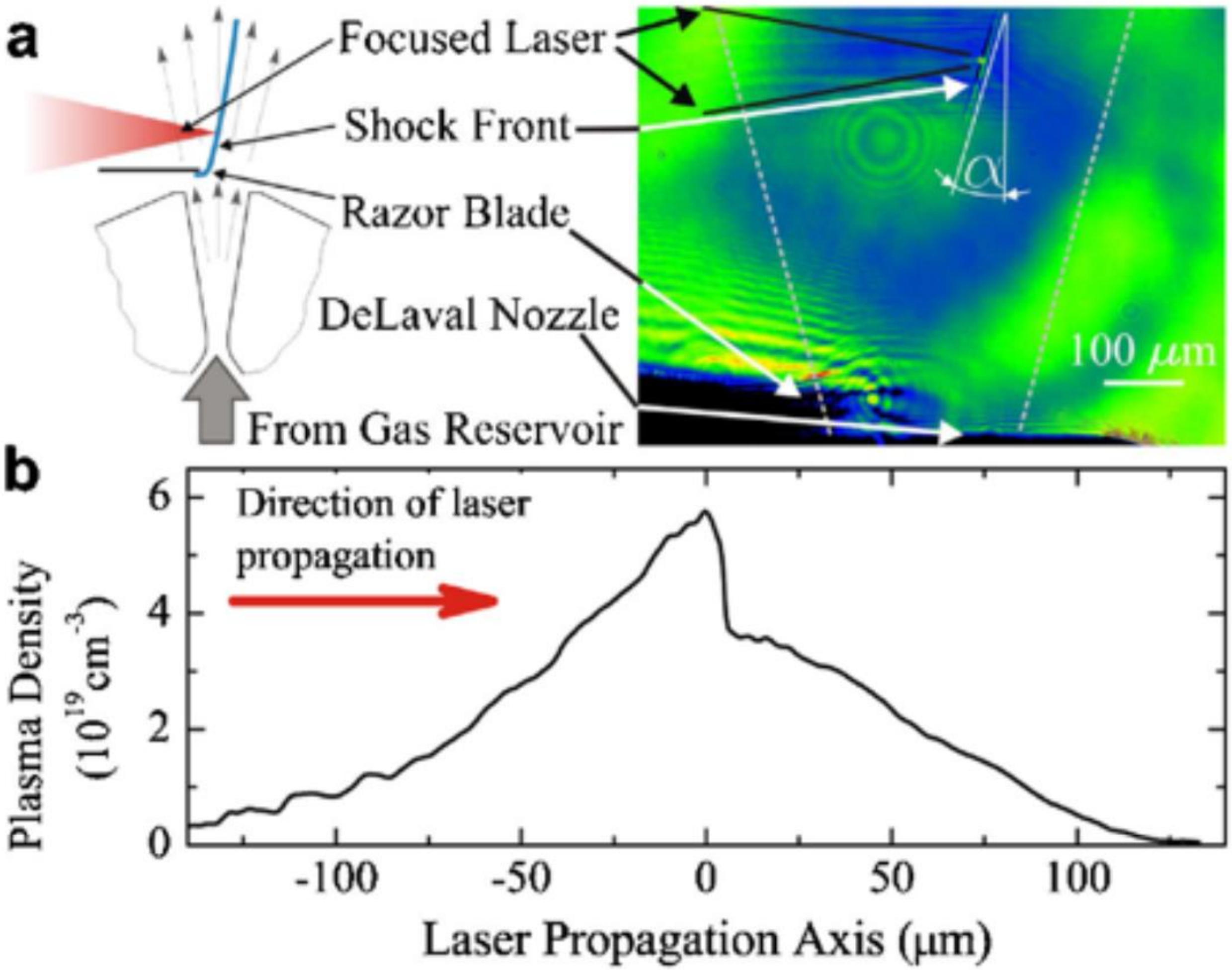


- Down-ramp injection: laser is focused into the area of decreasing density
- In this case the length of the bubble will grow for certain time
- Electrons which were on the boundary of trapping area will now appear inside of plasma bubble => more electrons will be trapped and accelerated
- Constant density region placed after the down-ramp allow to accelerate these electrons to high-energy

Bulanov PRE 1998, Geddes PRL 2008, Gonsalves Nature Physics 2011

From Stuart Mangles, JAI lecture on LWFA:
https://indico.cern.ch/event/758617/contributions/3146206/attachments/1751792/2838723/Wakefield_intro.pdf

Down-ramp injection



Sharp profiles in plasma density can be achieved using obstructed supersonic gas jets

Schmid PRSTAB 2010

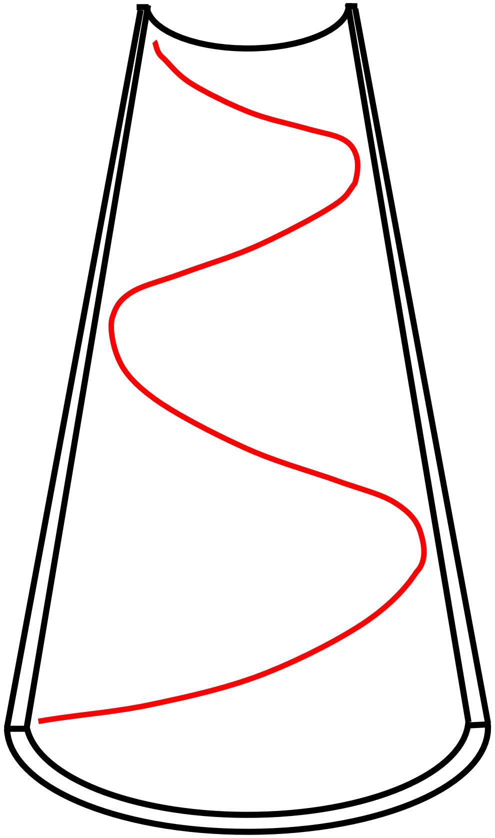
From Stuart Mangles, JAI lecture on LWFA:
https://indico.cern.ch/event/758617/contributions/3146206/attachments/1751792/2838723/Wakefield_intro.pdf

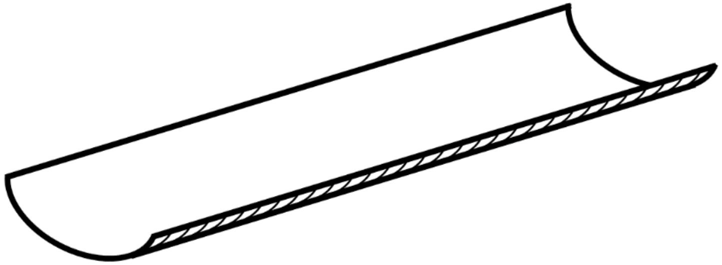
Phenomena affecting LWFA

- **As laser propagates through the gas/plasma, several competing effects are important**
  - **Dephasing**
  - **Depletion**
  - **Longitudinal compression by plasma waves**
  - **Self focusing**
    - **Including relativistic effect – electrons of plasma at centre become relativistic and have higher mass**
  - **Diffraction**
    - **Small laser beam (~30μm) will diffract very fast**
    - **Includes ionization caused diffraction (centre where intensity is higher ionized first)**

- **Re-inventing the way to solve many of these problems**
  In particular, how to overcome diffraction and keep laser beam focused and propagated for considerable distance?
  Can you suggest a way?

Re-inventing LWFA



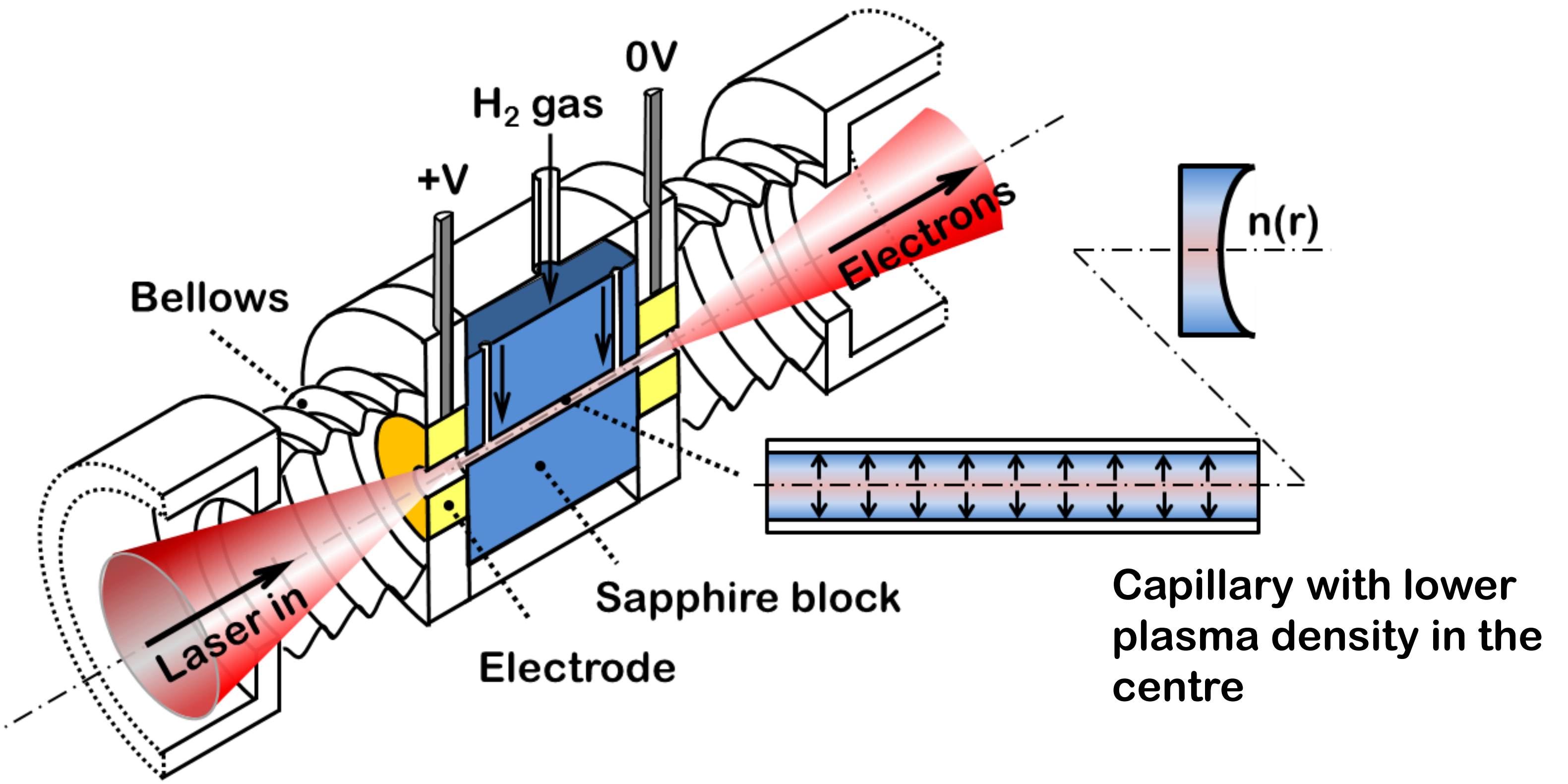


Hint: try to use resources that you already have in the system
& look at these analogies

Importance of laser guidance

- **As laser propagates through the gas/plasma, several competing effects are important**
  - **Dephasing**
  - **Depletion**
  - **Longitudinal compression by plasma waves**
  - **Self focusing**
    - **Including relativistic effect – electrons of plasma at centre become relativistic and have higher mass**
  - **Diffraction**
    - **Small laser beam (~30μm) will diffract very fast**
    - **Includes ionization caused diffraction (centre where intensity is higher ionized first)**
- **A possible solution – create a channel with plasma density profile n(r) to guide laser**
  - **A particular solution – capillary discharge channel developed in Oxford**

Importance of laser guidance



Capillary channel designed by Prof Simon Hooker

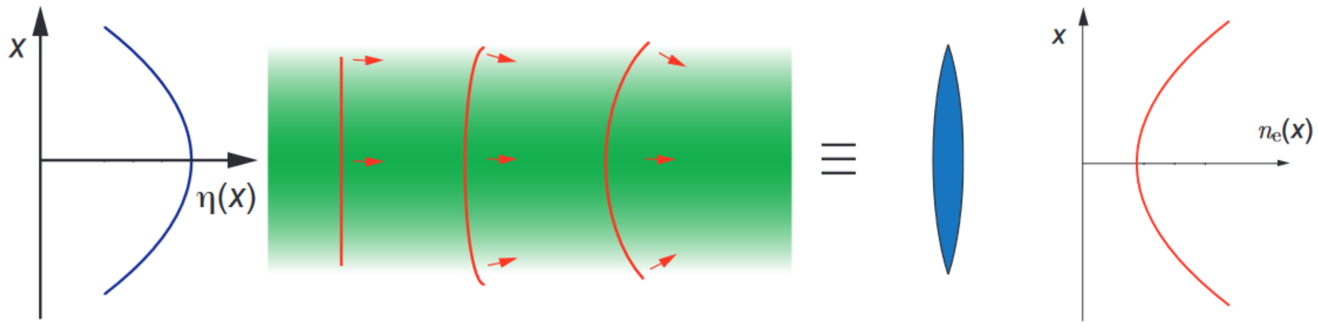
- **Capillary channel allowed exceeding 1GeV laser plasma acceleration for the first time**

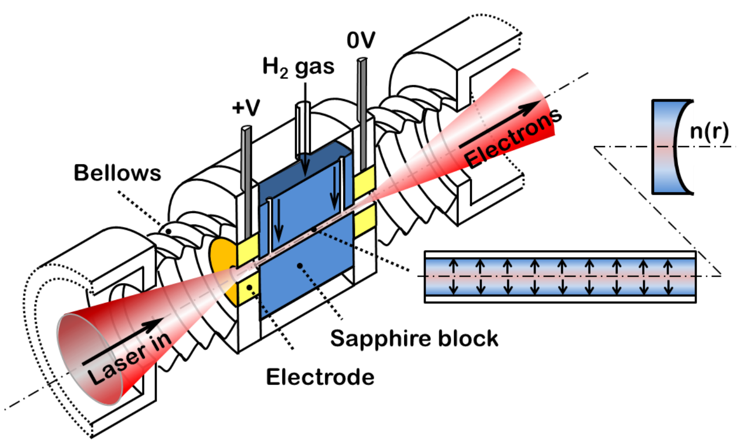
Importance of laser guidance

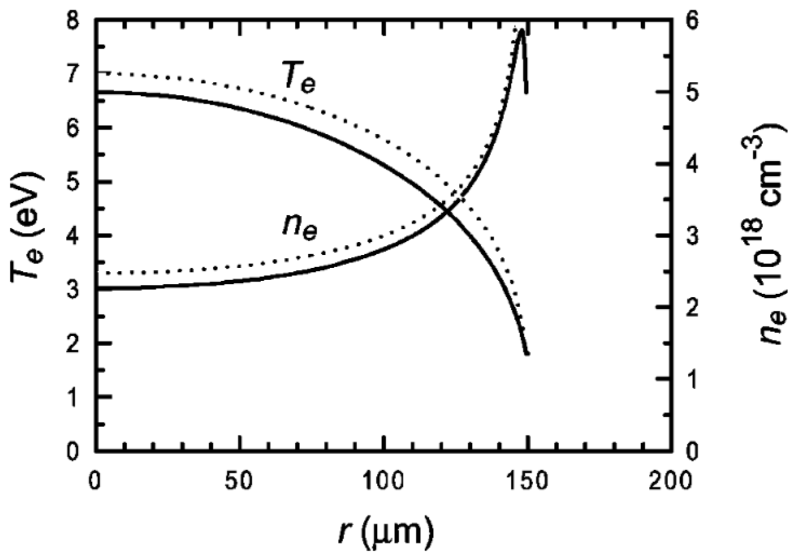
Plasma
refractive index:

$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2}$$

$$\approx 1 - \frac{1}{2}\frac{n_e(r) e^2}{\gamma m_e \epsilon_0 \omega^2}$$





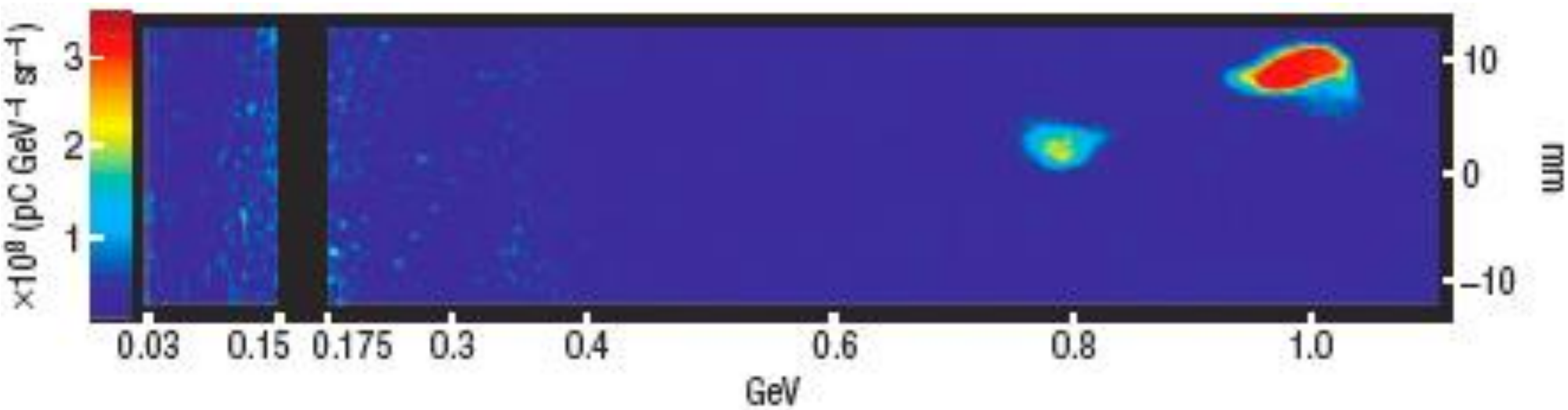


N. A. Bobrova, et al., Phys. Rev. E 65, 016407, 2001, https://journals.aps.org/pre/pdf/10.1103/PhysRevE.65.016407

From Simon Hooker, JAI Adv Board 2019, https://indico.cern.ch/event/802186/contributions/3334745/attachments/1807938/2951491/2019_JAI_AB_talk_Hooker.pdf

First ever 1 GeV from laser plasma accelerator

- **1 GeV acceleration & monoenergetic beam**
  - **Use of guiding capillary was essential**

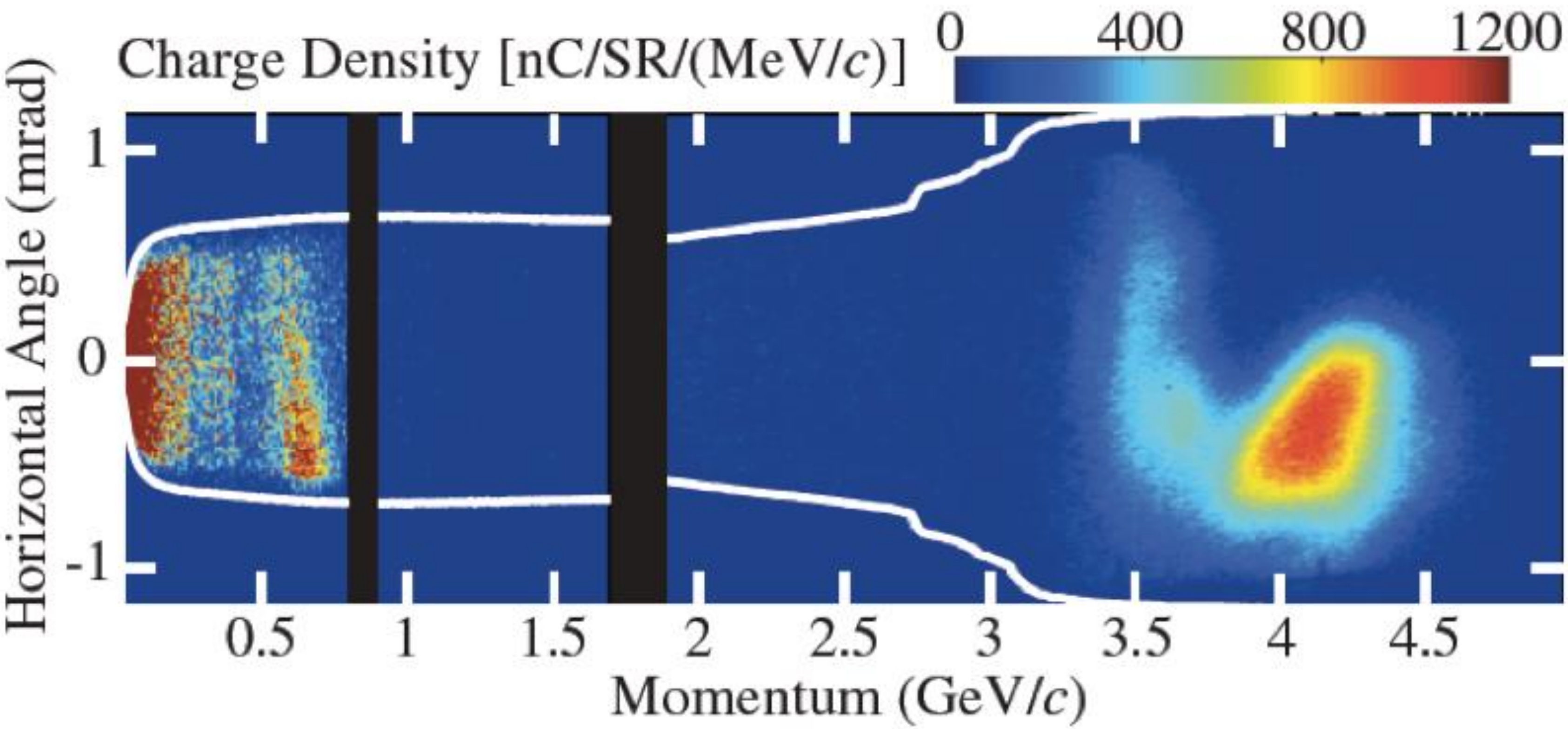


1GeV acceleration in just 3cm of plasma

W. Leemans, B. Nagler, A. Gonsalves, C. Toth, K. Nakamura, C. Geddes, E. Esarey, C. B.Schroeder, & S. Hooker, ***Nature Physics*** 2006

Plasma density 2.7×10^{18} cm^{-3}, 40 TW laser with 10^{18} W/cm^2

Further energy record

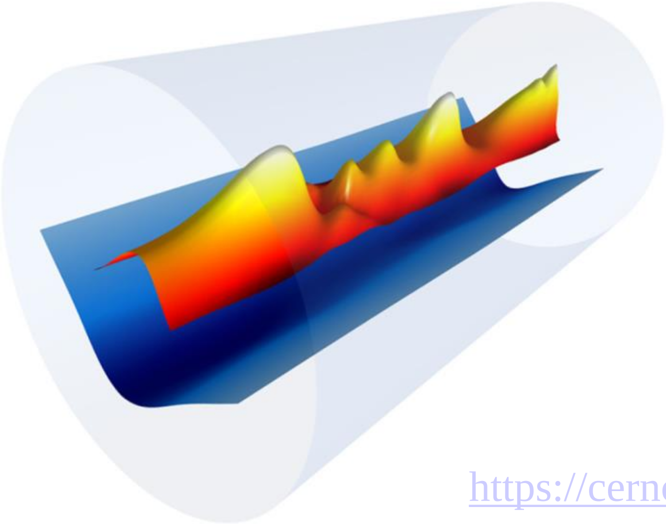


4.2 GeV, 2014

W. Leemans et al., PRL 113, 245002 (2014)

Multi-GeV from laser plasma accelerator

- **7.8 GeV acceleration & monoenergetic beam**
  - **Use of guiding capillary was essential, and increasing the focusing strength of a capillary discharge waveguide using laser inverse bremsstrahlung heating**



The plasma channel's electron density profile (blue) formed inside a sapphire tube (grey) with the combination of an electrical discharge and ultrashort laser pulse (red, orange, and yellow). Credit: G Bagdasarov/A Gonsalves/J-L Vay and CERN Courier

https://cerncourier.com/a/bella-sets-new-record-for-plasma-acceleration/

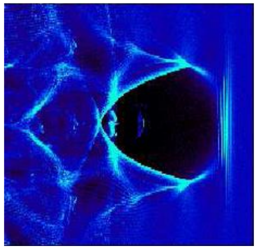
A Gonsalves *et al*. 2019 *Phys. Rev. Lett*. **122** 084801.

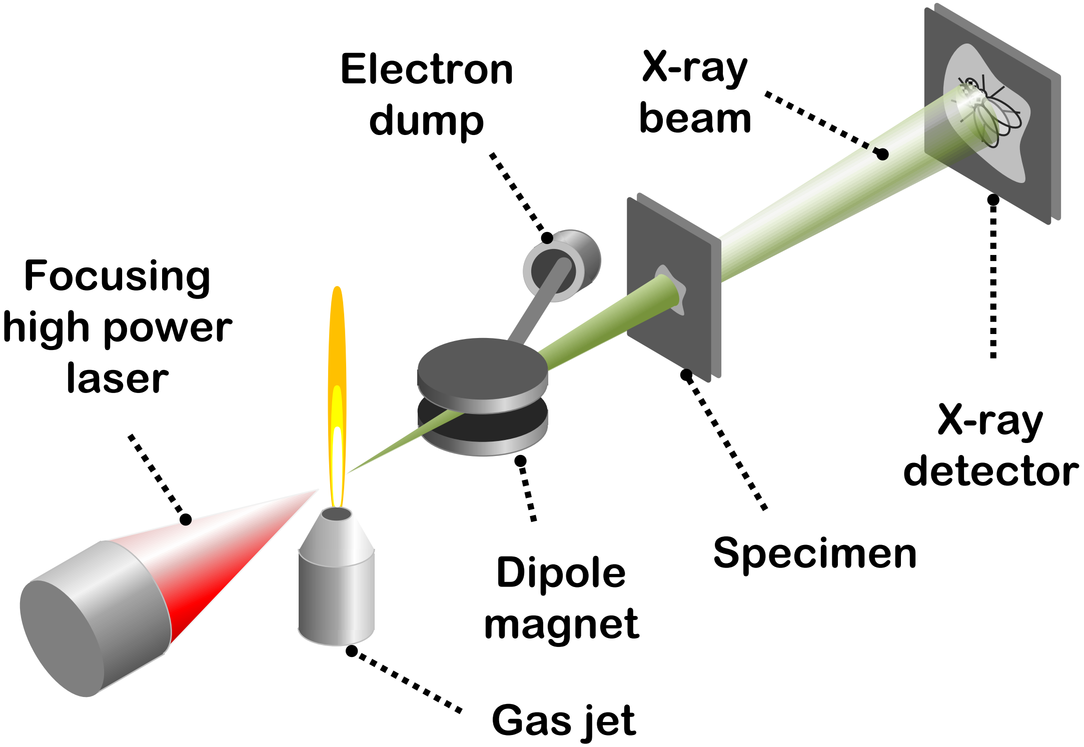
Laser Plasma accelerator

Modern synchrotrons-based light sources are big machines (several 100s meters)

Provided that we solve the challenges of stability, efficiency and repetition rate, we can create, based on plasma acceleration, compact (~10m) light sources – betatron X-ray and eventually an FEL

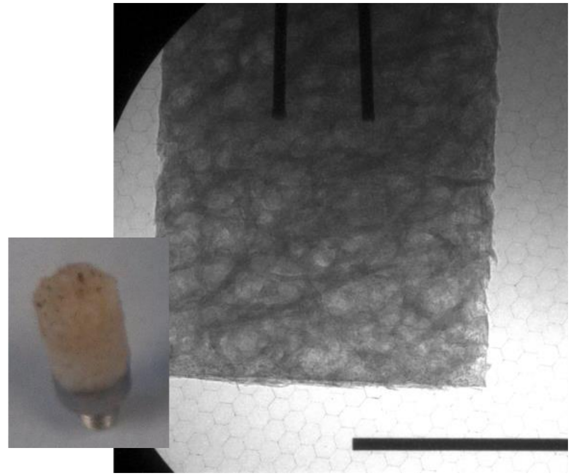
Similar electron energies (3-6 GeV) as in synchrotrons, can be reached in a much more compact plasma accelerator using the "wake" created by a laser in a gas jet.



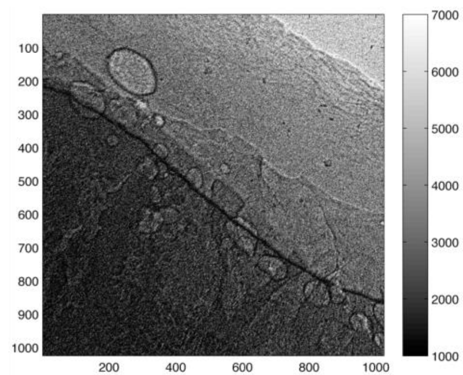


Medical imaging with LWFA betatron light source

- **Betatron radiation could prove to be an interesting source for medical radiography**
  - **Small source size and collimated beam allows for high resolution phase contrast imaging of soft tissue, e.g. breast, prostate…**
  - **Hard photon energy with small source size allows for high resolution imaging of bone, biological samples**

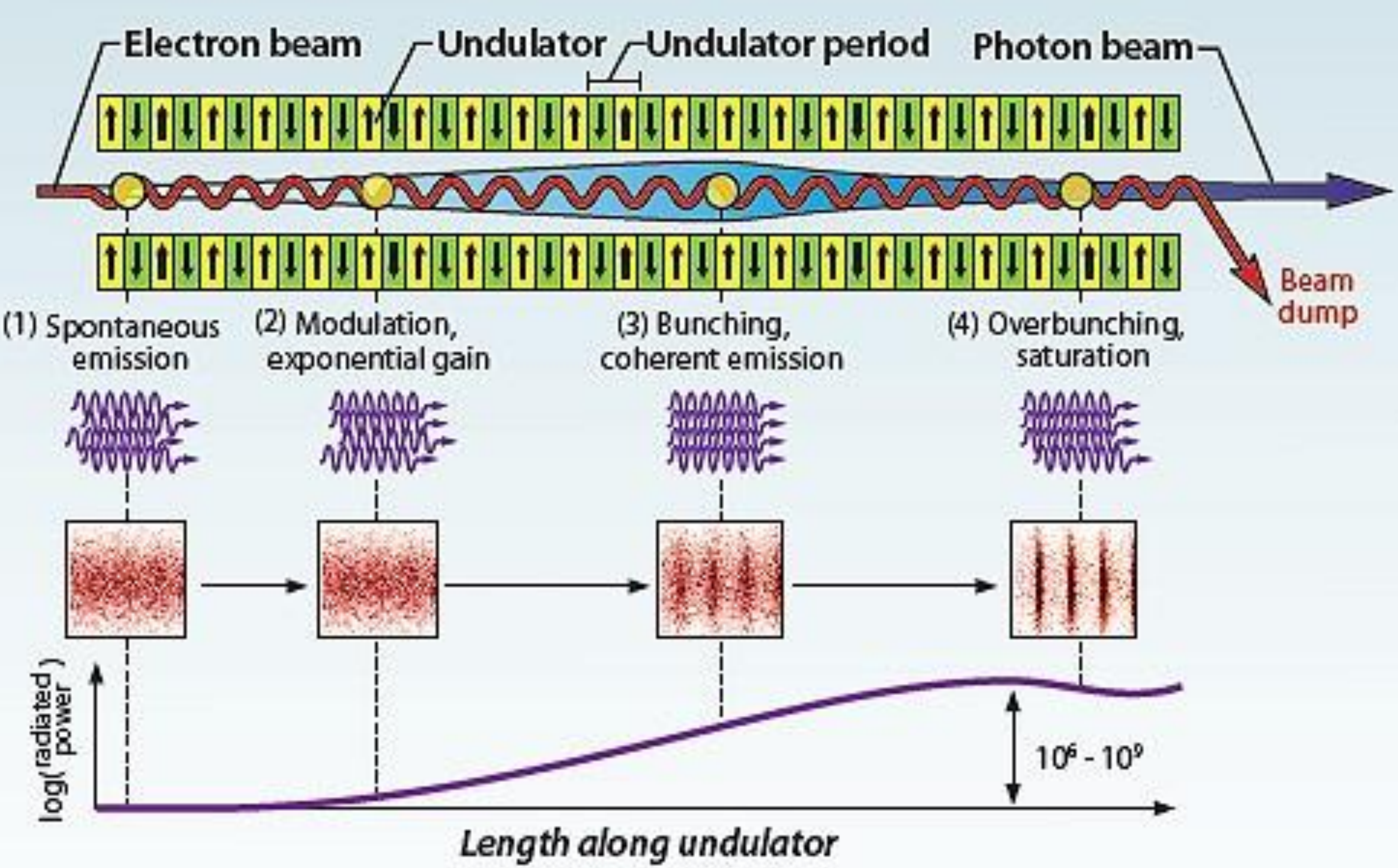


X-ray radiograph of femural bone sample (left, and photo inset) tomographically reconstructed (right)



Phase-contrast imaging of prostate (left) and tomograph of pre-natal mouse (right)

4th generation light source – Free Electron Laser Overview



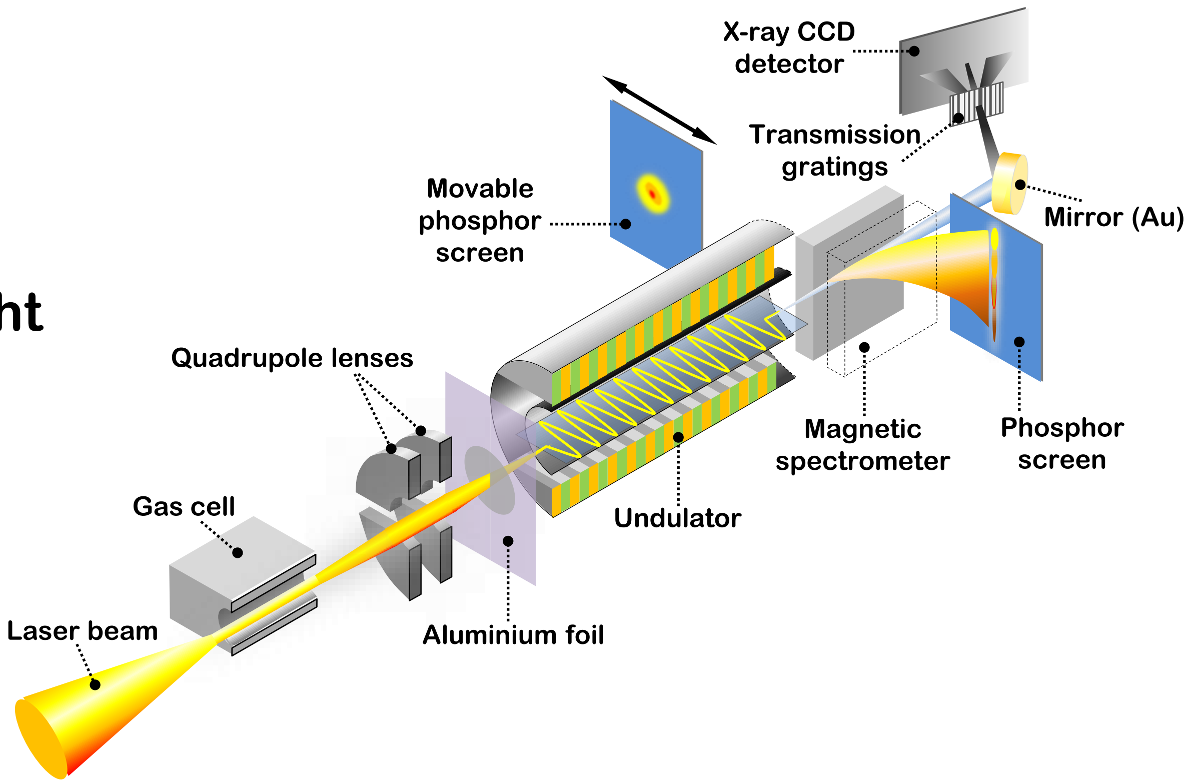
Beyond fourth generation light sources

The progress with laser plasma accelerators in the last years have open the possibility of using them for the generation for synchrotron radiation and even to drive a FELs

Many observations of undulator radiation achieved in Soft X-ray

FEL type beam can be achieved with relatively modest improvements on what presently achieved and significant improvement on the stability of these beams

Layout of a compact light source driven by a LPWA



Plasma acceleration FELs – first lasing

"experimental demonstration of undulator radiation amplification in the exponential-gain regime by using electron beams based on a laser wakefield accelerator. The amplified undulator radiation, which is typically centred at 27 nanometres and has a maximum photon number of around 1E10 per shot, yields a maximum radiation energy of about 150 nanojoules. In the third of three undulators in the device, the maximum gain of the radiation power is approximately 100-fold, confirming a successful operation in the exponential-gain regime"

Free-electron lasing at 27 nanometres based on a laser wakefield accelerator, Wentao Wang, et al., 516 | Nature | Vol 595 | 22 July 2021

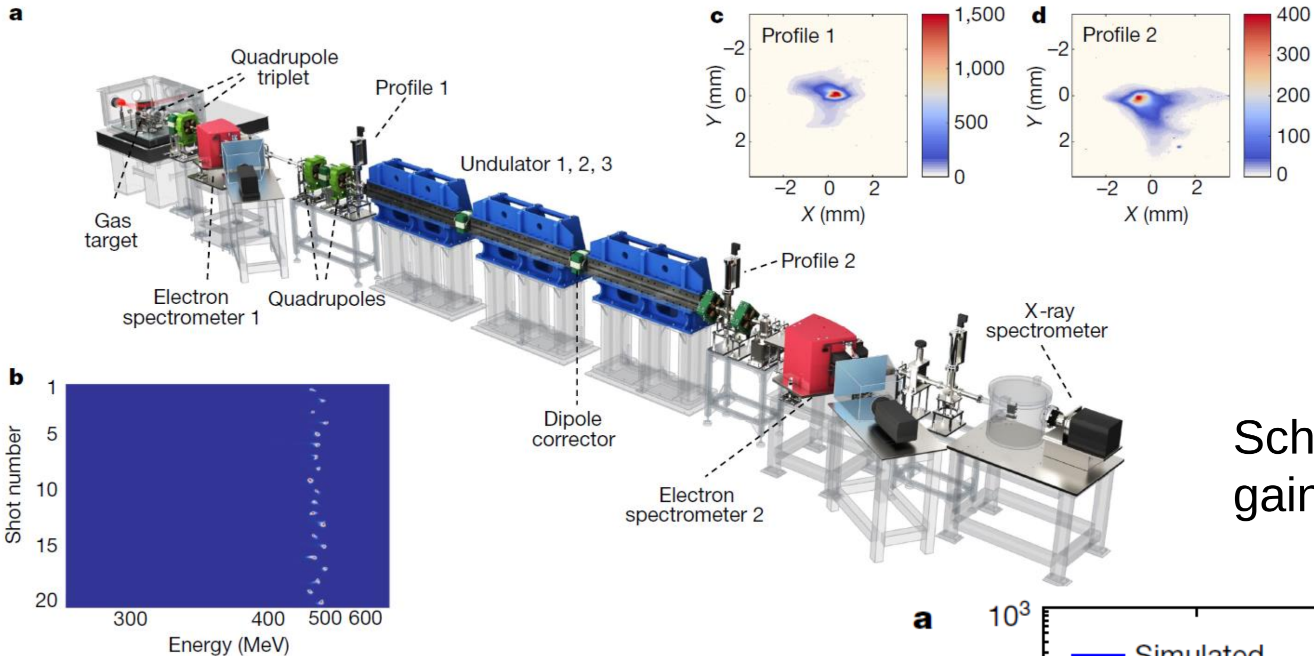
https://www.nature.com/articles/s41586-021-03678-x

"experimental evidence of FEL lasing by a compact (3-cm) particle-beam-driven plasma accelerator. … observation of narrow-band amplified radiation in the infrared range with typical exponential growth of its intensity over six consecutive undulators"

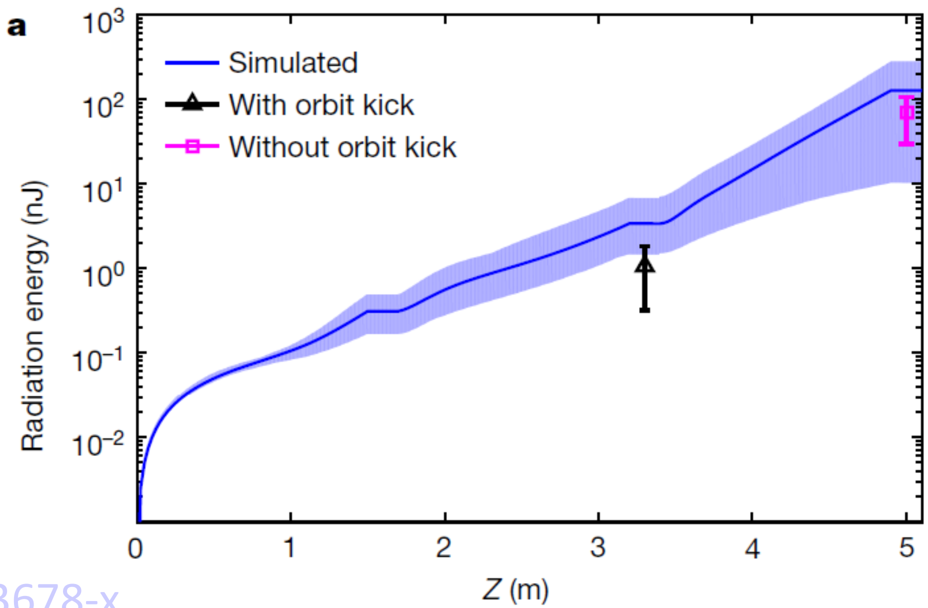
Free-electron lasing with compact beam-driven plasma wakefield accelerator, R. Pompili, D. Alesini, …M. Ferrario, Nature volume 605, pages 659–662 (2022)

https://www.nature.com/articles/s41586-022-04589-1

Plasma acceleration FELs – first lasing



Scheme and exponential gain measurements



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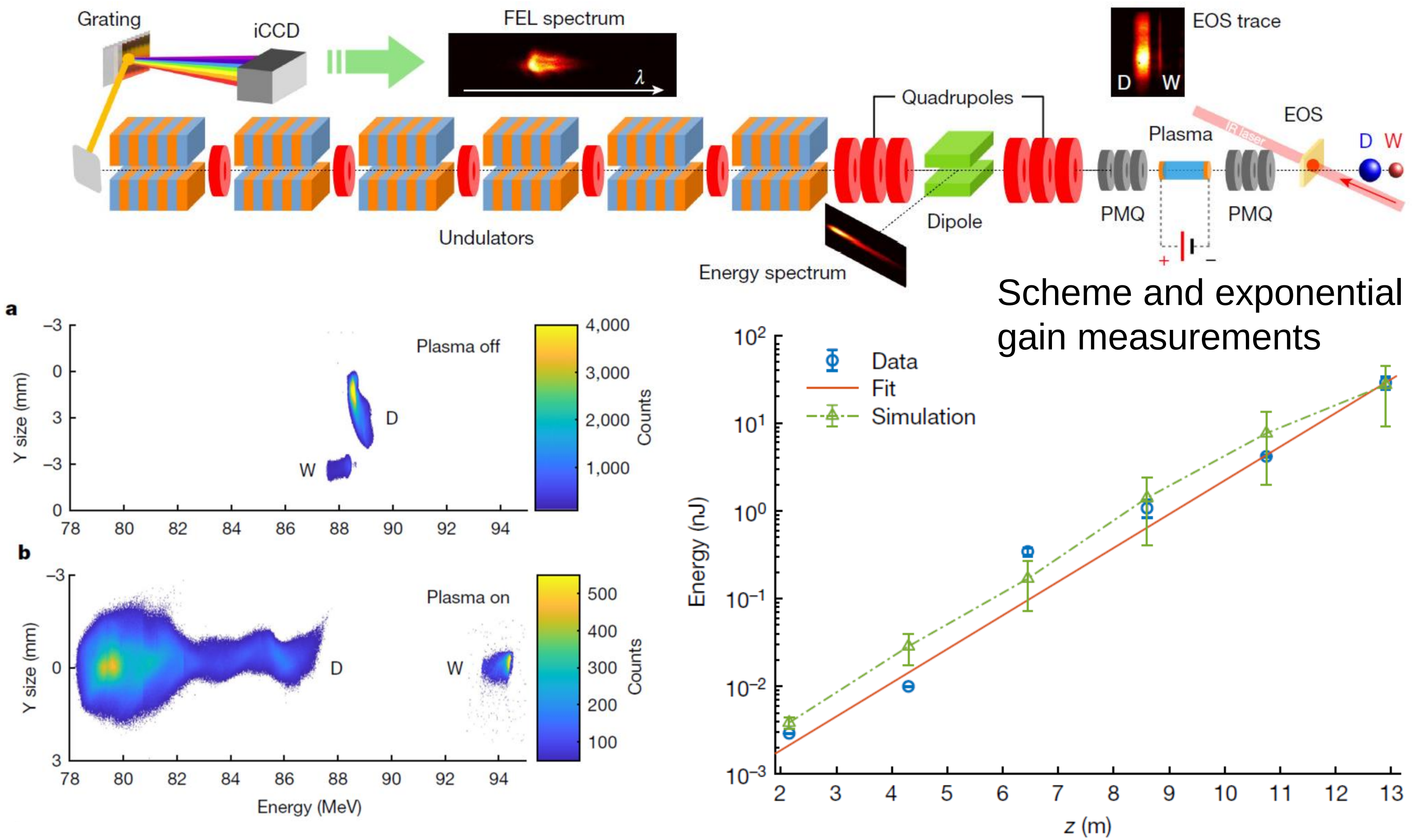
Plasma acceleration FELs – first lasing



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"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