# Accelerator Science and Technology via **Inventive Principles of TRIZ** Andrei Seryi **Jefferson Lab**

NA-PAC 2022, 10 August 2022

LHC sketches by Sergio Cittolin (CERN)

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  - https://ieee-npss.org/distinguished-lecturers/
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  - <u>https://www.unifyingphysics.com/</u>
- CERN for "eBook for all!" program that enabled conversion of the 1<sup>st</sup> edition of "Unifying Physics…" to open access



Jefferson National Accelerator Facility







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# Slides are available at

- https://www.unifyingphysics.com/



### – See section Resources

 You can also access the 1<sup>st</sup> edition of the book which is now Open Access Scientific revolutions – what drives them? Two points of view:

### Philosopher Thomas Kuhn: scientific revolutions are concept-driven

"paradigm shifts"

#### Physicist Freeman Dyson: scientific revolutions are tool-driven

"The human heritage that gave us toolmaking hands and inquisitive brains did not die. In every human culture, the hand and the brain work together to create the style that makes a civilization....

Science will continue to generate unpredictable new ideas and opportunities. And human beings will continue to respond to new ideas and opportunities with new skills and inventions. We remain toolmaking animals, and science will continue to exercise the creativity programmed into our genes."



We would like to make positive and proactive impact on the evolution of science and technology

Can we learn from past efforts to make our impact more reliable and efficient?

Demonstrating the new techniques of the think tanks, this book projects what our own world most probably will be like a generation from nowand gives alternatives.

AMEWORK

SPECULATION ON

THE NEXT THIRTY-THREE YEARS

by HERMAN KAHN and ANTHONY J. WIENER Introduction by DANIEL BELL

> "The Year 2000", 1968 K. Herman, A. Wiener ISBN 978-0025604407

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Can the methodology of predictions be reliable?

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# Lesson: avoid naïve extrapolations

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Predictions made in 1968 for the year 2000, examples:

1- Multiple applications of lasers for sensing, communication, cutting, welding...

**31- Some control of weather and/or climate** 

35 – human hibernation for extensive periods (months to years)

"The Year 2000", 1968 K. Herman, A. Wiener ISBN 978-0025604407



58- Chemical methods for improving memory and learning

67- Commercial extraction of oil from shale

81- Personal "pagers" and perhaps even two-way pocket phones

99- Artificial moon for lighting large areas at night

Some predictions were accurate, some not

THE year 2000

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1- Multiple applications of lasers for sensing, communication, cutting, welding...

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Some predictions were accurate, some not

THE year 2000

#### Chengdu to launch "artificial moon" in 2020 (People's Daily Online) 09:06, October 16, 2018

"Southwestern China's city of Chengdu plans to launch its illumination satellite, also known as the "artificial moon", in 2020, according to Wu Chunfeng, chairman of Chengdu Aerospace Science and Technology Microelectronics System Research Institute Co., Ltd. ... The illumination satellite is designed to complement the moon at night. Wu introduced that the brightness of the "artificial moon" is eight times that of the real moon, and will be bright enough to replace street lights. The satellite will be able to light an area with a diameter of 10 to 80 kilometers, while the precise illumination range can be controlled within a few dozen meters. ...The testing of the illumination satellite started years ago, and now the technology has finally matured, explained Wu. Some people expressed concern that the lights reflected from space could have adverse effects on the daily routine of certain animals and astronomical observation. Kang Weimin, director of the Institute of Optics, School of Aerospace, Harbin Institute of Technology, explained that the light of the satellite is similar to a dusk-like glow, so it should not affect animals' routines."

http://en.people.cn/n3/2018/1016/c90000-9508748.html

To make viable predictions and efficient research plans:

Learn from the past of this particular area of science... ...but also look around, across different disciplines and areas of science...

And, possibly, use "Breakthrough By Design" approach...

...not only for prediction, but for pro-actively shaping the future

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# **Evolution laws and inventive principles**

Are there some patterns in evolution of scientific and engineering systems and instruments?

Are there some general inventive principles that connect different instruments/systems in different areas?

Let's look at some examples from a new angle

# **Two scientific instruments**



# LIGO, Hanford

#### SLC, Stanford

## What is in common?

#### 2017 Nobel Prize in Physics – gravitational waves



Source: PRL 116, 061102 (2016)

Image: Caltech/MIT/LIGO Lab





# These two instruments

LIGO: keep two objects placed 4km apart stable\* to about 1e-9 nm

#### CLIC –

Compact Linear Collider: keep 100,000 objects distributed over 50km stable\* to about 10 nm



# \*) approximately, and in certain frequency range

# **CLIC stability & LIGO test mass isolation**



#### Nested stabilization/alignment systems of CLIC two-beam module

#### **Nested pendulums of LIGO**

Source: arXiv:1102.3355

# **CLIC stability & LIGO test mass isolation**



... connected via an inventive principle – let's call it the principle of "nested dolls"

# Particle or gravitational waves detectors are arranged just as nested dolls...



# Examples of "nested dolls" *inventive principle* can be found in various areas

Unifying physics, 2022, A. Seryi, JLab

# The principle of "nested dolls" in poetry

#### "This is the house that Jack built"

This is the house that Jack built.

This is the malt That lay in the house that Jack built.

This is the rat, That ate the malt That lay in the house that Jack built.

This is the cat, That killed the rat, That ate the malt That lay in the house that Jack built.

This is the dog, That worried the cat, That killed the rat, That ate the malt That lay in the house that Jack built.

This is the cow with the crumpled horn, That tossed the dog, That worried the cat, That killed the rat, That ate the malt That lay in the house that Jack built.





This is the maiden all forlorn, That milked the cow with the crumpled horn, That tossed the dog, That worried the cat, That worried the cat, That ate the malt That ate the malt That lay in the house that Jack built.

This is the man all tattered and torn, That kissed the maiden all forlorn, That milked the cow with the crumpled horn, That tossed the dog, That worried the cat, That killed the rat, That tae the malt That lay in the house that Jack built.

This is the priest all shaven and shorn, That married the man all tattered and torn, That kissed the mailen all forlorn, That milked the cow with the crumpled horn, That tossed the dog, That worried the cat, That killed the rat, That tate the mail That lay in the house that Jack built.

This is the cock that crowed in the morn, That waked the priest all sharen and shorn, That married the man all tattered and torn, That milked the cow with the crumpled horn, That milked the cox, That worked the cat, That worked the cat, That at the mails mails that hat he the

This is the former source blaccore, That key the cost that crowed in the more, That wands the privat all shaven and altern. That married how much list and and son, That shared the much all forlows, That shared the cost with the cost That share the cost with the cost That share the cost of the cost That share the cost of the cost That share the cost of the cost That share the cost that Jack built.

Mother Goose Rhymes

Illustration by Olga Rubtsova (Atroshenko)

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This is the farmer aceing his core, That key the occle that crowed in the more, That waked the privat all abuves and shorn. That married hermal fattered and stry, That falled the scale all forlow, That falled the core with the complete horn That working the core with the scale That working the care, That king the rate, That king the houses that Jack hull.

Mother Goose Rhymes

#### Is there any example of this principle in science fiction?

# The principle of "nested dolls" in sci-fi poetry

Valery Bryusov – 1920 poem "Atom" ("The World of Electron")

Can you imagine that electrons Are planets circling their Suns? Space exploration, wars, elections And hundreds of computer tongues

Быть может, эти электроны Миры, где пять материков, Искусства, знанья, войны, троны И память сорока веков!

Remake-translation by A.Seryi

Ещё, быть может, каждый атом — Вселенная, где сто планет; Там — всё, что здесь, в объёме сжатом, Но также то, чего здесь нет.

# Is there world inside of an electron?



#### Accelerators and detectors can help to understand whether there is a world inside of an electron



#### invented in 1911

Unifying physics, 2022, A. Seryi, JLab

Slides: https://www.unifyingphysics.com/

## **Cloud and bubble chambers**



Wilson's Cloud chamber invented in 1911 Bubbles of liquid in a gas Glaser's Bubble chamber, invented in 1952 Bubbles of gas in a liquid

These two instruments are connected via another inventive principle – "the other way around" or "system and anti-system"

## **Cloud and bubble chambers**



Wilson's Cloud chamber invented in 1911 Bubbles of liquid in a gas Glaser's Bubble chamber, invented in 1952 Bubbles of gas in a liquid

Bubble chamber could have been invented immediately, and not 40 years later after the cloud chamber, if we would have applied the principle of "system and anti-system"

# System-anti-system and focusing in accelerators

Focusing is needed to keep the particle trajectories near the centre

The analogy with the motion in the gutter







The first accelerators had weak focusing with spatial period greater than the perimeter of the accelerator

The trajectories of particles in an accelerator with weak focusing





# Weak focusing accelerator

10 GeV weak-focusing Synchrophasotron built in Dubna in 1957, the biggest and the most powerful for its time. It is ~60m diameter ring, and its magnets weigh 36,000 tons and it was registered in the Guinness Book of Records as the heaviest in the world.

View inside of the magnets. Vacuum chamber, which occupied all this space, now removed.

# Dreaming big



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

#### Imagine how humongous it would be if it would be built as a weak focusing machine!

# Focusing

Focusing is needed to keep the particle trajectories near the centre

The analogy with the motion in the gutter







In this analogy, can we bend the gutter stronger, to achieve strong focusing?

The trajectories of particles in an accelerator with weak focusing

# Weak and strong focusing



# Weak and strong focusing


#### Weak and strong focusing



#### Weak and strong – compare them



10 GeV weak-focusing Synchrophasotron built in Dubna in 1957, the biggest and the most powerful for his time. It is ~60m diameter ring, and its magnets weigh 36,000 tons and it was registered in the Guinness Book of Records as the heaviest in the world. CERN's Proton Synchrotron, the first operating strong-focusing accelerator, reached 24 GeV in 1959. It is a ~200-m diameter ring, weight of magnets 3,800 tons.

## The structure of matter...



#### ...use particles



#### ...use particle accelerators



#### Chemistry Nobel 2014 & inventive principles?



#### Chemistry Nobel 2014 ...

Stimulated Emission Depletion microscopy (STED) Stefan W. Hell



#### This can improve the resolution to be a factor of several below the wavelength of light

confocal

standard confocal image

gSTED

#### **Chemistry Nobel 2014 & inventive principles**



# And this can be viewed as a combination of the inventive principles "system and anti-system" and "nested dolls"

#### Nobel prize 2018 – CPA

#### Arthur Ashkin, Gérard Mourou and Donna Strickland



Image: Johan Jarnestad/Royal Swedish Academy of Sciences

#### Is there an inventive principle here that is used in other areas?

#### Chirped pulse amplification from Radar to Lasers (CPA)

Diagrams taken from early LLE review On the comparison between RADAR chirped pulse amplification from the 1940 onwards upper diagram and laser chirped pulse amplification bottom diagram carried out at the LLE Rochester. (b)  $rac{cw}{mode-locked}$  laser  $rac{1}{4}$   $rac{1}{4}$  $rac{$ 

Slide from Bob Bingham, CLF, STFC

LLE Review 25 3B 1985.

#### **CPA – Chirped Pulse Amplification**



CPA: pulse stretching and compressing using time-energy correlation

#### **Beam and laser bunch/pulse compression**



Both in laser and beam use z-Energy correlation to compress/stretch the pulse – this seem to be one more general inventive principle – connecting laser CPA and particle accelerators

#### **Radar and CPA**

Evolution from chirped pulse amplification in radars to lasers, and connection of CPA with bunch compression in accelerators, seem to demonstrate that ...

The same Problems and Inventions appear again and again but in different areas of science and technology

#### Let's now talk about inventiveness

We have seen several examples of what seem to be some general inventive principles and evolution laws

It happens that many of such inventive principles and evolution laws are known for half a century and widely used... ...but so far not in science

Let's discuss methodologies of inventiveness

## How to invent more efficiently?

#### **Forbes**



TECH | 3/07/2013 @ 6:32AM | 72,570 views

What Makes Samsung Such An Innovative Company? What was that magic bullet? ...wait a few slides...

But it was that became the bedrock of innovation at Samsung. And it was introduced at Samsung by whom Samsung had hired into its Seoul Labs in the early 2000s.

In 2003 led to 50 new patents for Samsung and in 2004 one project alone, a DVD pick-up innovation, saved Samsung over \$100 million. now an obligatory skill set if you want to advance within Samsung.

is

#### How to invent – evolution of the methods

- Brute-force or exhaustive search
  - consider any possible ideas
- Brainstorming
  - psychological method which helps to solve problems and to invent
  - The main feature of brainstorming separate the process of idea generation from the process of their critical analysis
  - The method of brainstorming did not meet expectations
    - the absence of feedback, which is the power of the method, is simultaneously its handicap, as feedback is needed for development and adjusting of an idea



Alex Osborn (1888 – 1966)

The author of brainstorming Alex Osborn introduced the method around 1950s

#### How to invent – evolution of the methods

- Synectics improved Brainstorming
- Features of Synectics:
  - Permanent groups for problem solving
    - whose members with time become less sensitive to critics and more efficient in problem solving
  - Emphasis on the importance to see familiar behind unknown and vice versa
    - which should help to solve a new and unfamiliar problem with known methods
  - Importance of a fresh view at a problem
  - Use of analogies to generate fresh view
    - direct (any analogy, e.g. from nature);
    - empathic (attempting to look at the problem identifying yourself with the object);
    - symbolic (finding a short symbolic description of the problem and the object);
    - metaphorical (describing the problem in terms of fairy-tales and legends);



Attempting to improve brainstorming, George Prince (on the photo) and William Gordon introduced the method of Synectics

#### ILC Interaction Region...

Anti-solenoid is needed, but it would be pulled into the main solenoid with humongous force



#### **Synectics : use of analogies**

#### Use of <u>analogies</u> to generate fresh view

- ...
- empathic (attempting to look at the problem identifying yourself with the object);
- ..
- metaphorical (describing the problem in terms of fairy-tales and legends);

# How to contain the magnetic flux?



**ILC Interaction Region...** 



Unifying physics, 2022, A. Seryi, JLab

## Synectics and use of analogies

- Use of <u>analogies</u> to generate fresh view
  - ...
  - empathic

     (attempting to look at the problem identifying yourself with the object);
  - ...
  - metaphorical (describing the problem in terms of fairy-tales and legends);



#### Synectics does not help

#### How to invent – evolution of the methods

- Synectics is the limit of what can be achieved, maintaining the brute force method of exhaustive search
  - Indeed, why one would employ analogies and metaphors and irrational factors in order to come to a natural and universal formula "the action has to happen itself"

#### How to invent – evolution of the methods

- Synectics is the limit of what can be achieved, maintaining the brute force method of exhaustive search
  - Indeed, why one would employ analogies and metaphors and irrational factors in order to come to a natural and universal formula "the action has to happen itself"
  - One should aim at such formula in any invention, armed with precise identification of physical contradiction – essence of <u>TRIZ</u>



## How to invent – TRIZ

- TRIZ Teoria Reshenia Izobretatelskikh Zadach
- = 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



Genrikh Altshuller (aka Altov)1926-1998

## How to invent – TRIZ

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  - 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:



Genrikh Altshuller (aka Altov)1926-1998

- The <u>same Problems and Solutions</u> appear again and again but in <u>different industries</u>
- There is a recognisable <u>Technological Evolution path</u> for all industries
- Innovative patents (23% of total) used science/engineering theories outside their own area/industry
- An Innovative Patent <u>uncovers and solves contradictions</u>

## How to invent more efficiently?

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Haydn Shaughnessy, Contributor I write about enterprise innovation.

TECH | 3/07/2013 @ 6:32AM | 72,570 views

What Makes Samsung Such An Innovative Company? Why are we interested in this in relation to science? ...wait a few more slides...

But it was TRIZ that became the bedrock of innovation at Samsung. And it was introduced at Samsung by Russian engineers whom Samsung had hired into its Seoul Labs in the early 2000s.

In 2003 TRIZ led to 50 new patents for Samsung and in 2004 one project alone, a DVD pick-up innovation, saved Samsung over \$100 million. TRIZ is now an obligatory skill set if you want to advance within Samsung.



Example: following J.Scanlan, School of Engineering Sciences, Univ. of Southampton

#### **Elements of TRIZ contradiction matrix**

- 1. Weight of moving object
- 2. Weight of stationary object
- 3. Length of moving object
- 4. Length of stationary object
- 5. Area of moving object
- 6. Area of stationary object
- 7. Volume of moving object
- 8. Volume of stationary object
- 9. Speed
- 10. Force (Intensity)
- 11. Stress or pressure
- 12. Shape
- 13. Stability of the object
- 14. Strength
- 15. Durability of moving object
- 16. Durability of non moving object
- 17. Temperature
- 18. Illumination intensity
- 19. Use of energy by moving object
- 20. Use of energy by stationary object

- 21. Power
- 22. Loss of Energy
- 23. Loss of substance
- 24. Loss of Information
- 25. Loss of Time
- 26. Quantity of substance/the
- 27. Reliability
- 28. Measurement accuracy
- 29. Manufacturing precision
- 30. Object-affected harmful
- 31. Object-generated harmful
- 32. Ease of manufacture
- 33. Ease of operation
- 34. Ease of repair
- 35. Adaptability or versatility
- **36. Device complexity**
- 37. Difficulty of detecting
- 38. Extent of automation
- 39. Productivity

# Only 39 Matrix parameters!!!

#### **TRIZ Inventive Principles**

- 1. Segmentation
- 2. Taking out
- 3. Local quality
- 4. Asymmetry
- 5. Merging
- 6. Universality
- 7. Russian dolls
- 8. Anti-weight
- 9. Preliminary anti-action
- **10. Preliminary action**
- 11. Beforehand cushioning
- 12. Equipotentiality
- 13. "The other way round"
- 14. Spheroidality Curvature
- 15. Dynamics
- 16. Partial or excessive actions
- **17. Another dimension**
- **18. Mechanical vibration**
- **19. Periodic action**
- 20. Continuity of useful action

- 21. Skipping
- 22. Blessing in disguise
- 23. Feedback
- 24. Intermediary
- 25. Self-service
- 26. Copying
- 27. Cheap short-lived objects
- 28. Mechanics substitution
- 29. Pneumatics and hydraulics
- 30. Flexible shells and thin films
- 31. Porous materials
- 32. Colour changes
- 33. Homogeneity
- 34. Discarding and recovering
- 35. Parameter changes
- **36. Phase transitions**
- 37. Thermal expansion
- 38. Strong oxidants
- 39. Inert atmosphere
- 40. Composite materials

#### Only 40 Principles !!!

#### **TRIZ Principles and Contradiction matrix**

#### For our example with the lens:



## **TRIZ in action - example**

- Perform lookup\* of TRIZ Matrix for this contradiction:
  - Improving 9: SPEED without damaging 17: TEMPERATURE
- Find Principles to solve this contradiction:
  - 2. Taking out
  - 28. Mechanics substitution
  - 30. Flexible shells and thin films

#### - 36. Phase transitions





Abrasive + Ice - Inventive Principle 'Phase Transition'

\*) E.g. at http://www.triz40.com/

## **TRIZ for Universities**

#### Can TRIZ be useful in university education?



Unifying physics, 2022, A. Seryi, JLab

#### Can TRIZ be used in university education? Yes, and very successfully **U.S. Particle Accelerator School** Education in Beam Physics and Accelerator Technology Google" Custom Search **Course Materials** Tutorials Home About Programs Photos Opportunities Contact m USPAS **Current Program** A USPAS school project Compact ring-based X-ray source with class USPAS sponsored by on-orbit and on-energy laser-plasma gets the University of California, Davis January 16-27, 2017 an niection held in Rohnert Park, California oral Marlene Turner, Auraloe Edelen, Andrei Seryi, Jeremy Cheatam Osip Lishlin, Aakash Ajit Sahai, Brandon Zerbe, talk Andrew Laple, Chun Yan Jonathan Wong, Kai Shih, James Gerity, View Details >> at Gerard Lawler, Kookjin Moon NAPAC APPLY NOW 2016 Hearty Next Program congratulations USPAS sponsored by to all! Northern Illinois University June 12-23, 2017

Class of graduate students, after one-week course on accelerators, lasers and plasma, and TRIZ, created a novel design and were invited to make a plenary invited presentation at the North American Particle Accelerator conference!

# Can TRIZ be used in university education?

#### Yes. However, some critics:

It is not always possible to use prescriptive step-by-step methods with pre-defined tables of contradictions...

> Expected critics: why only the first contradiction is addressed? Is it just a linear order correction? How can TRIZ help to come to breakthrough ideas like theory of relativity? Etc...

Arguably, the way to teach TRIZ in universities should be different than in industrial companies...

Maybe, the best way to introduce TRIZ to university is via the process of pro-active re-creation of TRIZ for science

## **TRIZ** for universities

#### Can be very useful

Pro-active re-creation of TRIZ for university is attempted in this book: - helps to connect different areas - helps to learn inventiveness methods



http://www.crcpress.com/product/isbn/9781482240580

However, this was just the first small step...

Creating TRIZ for science through the process of analysing and re-building TRIZ will also help us to study it proactively



Major components of TRIZ that should be kept for applications to university education (in extended & redefined shape) are, to start with:

- inventive principles
- laws of evolution of systems
### 40 inventive principles in illustrations

- One can find many illustrations of inventive principles based on engineering examples
- On the next pages you will find illustrations based on accelerator science and some other areas of science
  - You will notice that some of the standard definitions of TRIZ principles are re-defined
  - Selected principles will be shown

See more details in:

Accelerating Science TRIZ inventive methodology in illustrations Elena Seraia, Andrei Seryi

arXiv:1608.00536 [physics.ed-ph] https://arxiv.org/abs/1608.00536

#### 7. Nested doll

Place one object inside another; place each object, in turn, inside the other.
Make one part pass through a cavity in the other.



#### 9. Preliminary anti-action

- If it will be necessary to do an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects.
  - Create beforehand stresses in an object that will oppose known undesirable working stresses later on.



٠

#### 13. The other way round

• Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it).

Make movable parts (or the external environment) fixed, and fixed parts movable.

Turn the object (or process) "upside down".



#### **Cloud and bubble chambers**

#### **35. Parameter changes**

Change an object's physical state (e.g. to a gas, liquid, or solid.)

- Change the concentration or consistency.
- Change the degree of flexibility. Change the temperature.
  - Change volume to surface ratio, etc.





15° C





## ...that was an example

... on how to make TRIZ more suitable for science

The principle "parameter change" can be interpreted very widely, and thus be very applicable to science

Define the "parameter" as the ratio of volume to surface area



# The principle of changing the volume to surface ratio



#### The same volume, but different surface area

## The principle of changing the volume to surface ratio



#### The same volume, but different surface area

The same principle is used in e+e- colliders, where "pancakes" are collided instead of "buns"





# The principle of changing the volume to surface ratio – an example



The same volume, but different surface area and the different amount of information ③

And could we suggest an example illustrating this principle, for instance, in biology?

# The principle of changing the volume to surface ratio – examples



## Keeping the same volume but increasing the surface area to enhance the functionality

# Inventive principles and fundamental symmetries

Including change of V/S into the principle "parameter change" connects it to fundamental symmetries, i.e. conservation laws of physics

$$\int_{\Delta V} d^3 x \boldsymbol{\nabla} \cdot \mathbf{A} = \oint_{\Delta S} \mathbf{A} \cdot d\mathbf{S}$$

Gauss theorem (divergence theorem): the total sources and sinks of a vectorial quantity, or the integral volume of its divergence, is equal to the net flux of this vectorial quantity across the volume boundary



## **Further adjustments**

#### What about quantum effects?

Can we (should we) include some inventive principles related to uncertainty principle, quantum entanglement, etc.?

Or what about energy recovery?

The method which enables many modern scientific instruments



## Inventing sci. instruments

Even if one would define a set of TRIZ inventive principles that would include many approaches used in science, would it be sufficient?

No

#### What would be missing?

Most importantly – the art of estimations

#### Example of back-of-the-envelope estimations

#### • Enrico Fermi (who was ~10 miles from the Trinity test):

- "About 40 seconds after the explosion the air blast reached me. I tried to estimate its strength by dropping from about six feet small pieces of paper before, during, and after the passage of the blast wave. Since, at the time, there was no wind I could observe very distinctly and actually measure the displacement of the pieces of paper that were in the process of falling while the blast was passing. The shift was about 2 1/2 meters, which, at the time, I estimated to correspond to the blast that would be produced by ten thousand tons of TNT"

 $\Box$ 

L

#### Importance of back-of-the-envelope estimations

#### They are important because

- they help to quickly check if your idea is viable obvious
- but even more important: they allow to improve cross-disciplinary understanding of scientists from different fields, like biology and physics

- To train yourself on back-of-envelope estimations one can consider various questions
- They do not have to be necessarily serious ;-)
- But the estimates should be based on a physical effect that is considered most important for a given question
- Making an estimate would also allow us to make invention how to improve a system

Importance of back-of-the-envelope estimations

- They are important because
  - they help to understand things better obvious
  - but even more important: they allow to improve cross-disciplinary understanding of scientists from different fields, like biology and physics
- What speed V is needed to reach height H and get to other side of the wall?



#### Importance of back-of-the-envelope estimations

 Estimate by requiring that during run along the wall the head would not fall to lower than half the height of the person...

You will then find  $V=H (g/h)^{1/2}$ 

or, for H=2m

V~4.7 m/s



:- )

#### **Applying an inventive principle**

- Once we made the estimation and understood the main challenge, we can solve the problem
- Apply inventive principle
- In this case #9 Preliminary anti-action
  - Two people running, second holding long stick to compensate action of gravity

## The art of estimating

Enrico Fermi was known for his ability to back-ofenvelope estimations

Many leading centers teach the art of estimating from school – e.g. the unique Phys-Math school in Novosibirsk





(Clockwise from top left) The Phys-Math School in Novosibirsk, Russia. Students deriving formulae during a class. Graduates of the 1963 class.

http://cerncourier.com/cws/article/cern/69910

There are books that can help to master the art of estimations, e.g. "Guesstimation 2.0" by Lawrence Weinstein (Old Dominion University)

#### **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**



#### 27. Cheap short-living objects

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



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



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

"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



#### **Consideration of use**



## **Synchrotron radiation light sources**

Synchrotron Radiation (SR) caused by leaving part of fields behind when the beam moves along the curve



#### Synchrotron radiation can be useful



Example of a structure of a virus decoded using SR



Diamond SR source at Harwell, UK

#### Synchrotron radiation on-the-back-of-theenvelope – power loss

Energy in the field left behind (radiated !):



#### Synchrotron radiation on-the-back-of-theenvelope –photon energy





A Microcomputer

for every one at Micro Price The MicroReal - 3 new generation The MicroReal - 3 new generation



"IBM bringing out a personal

computer would be like teaching an

elephant to tap dance" cca. 1981

Slides: https://www.unifyingphysics.com/

**Evolution of computers** and light sources



Compact university scale

light source

Future national scale light source

synumber of the paradigm

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

#### Incoherent SR => coherent





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"

Unifying physics, 2022, A. Seryi, JLab

# 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

where it analyses proteins synthesized by molecular machine, while the entire FEL is part of system super-system produces where it analyses patient-tailored molecular proteins synthesized by molecular machine machines for DNA repair Molecula **System** Sub-system Super-system machines for proteins synthesis 1 m?> 1 m 23 1 m 53 Molecular machines for proteins synthesis **PFFI** Microfluidic-Molecular LP FEL machines for DNA repair.

FEL is part of super-system

# 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

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



There are similar challenging and forward looking ideas based on technologies developed for the Electron-Ion Collider

## **Reiterate the main message**

- Breakthrough By Design approach re-formulated TRIZ combined with the art of estimations for connecting different areas of science & engineering
- Step by step development and implementation at various levels
  - Undergraduate, master, PhD courses, technical/industrial courses
  - With Natural Sciences, Engineering, Humanities
  - With nearby industry
  - cross silos, stronger connection between science and the needs of society
- Target audience
  - Undergraduates
  - Graduate student
  - Technical experts in the area
  - Veterans who are re-training for new career
- Possible implementation via traineeships or institutes
  - aim: connect different areas of science & industries with enhanced impact on all
  - composition: researchers, postdocs, industrial affiliates, innovation facilitators
  - connections: industry, science, business and investor angels
  - impact on science and industry, impact on society

# Let's look at some areas of accelerator S&T via inventive principles

#### We will see how much we can fit into the remaining time of this 2-hrs tutorial

## 1. Segmentation

- Divide an object into independent parts.
  - Make an object easy to disassemble.
- Increase the degree of fragmentation or segmentation.



## 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

Unifying physics, 2022, A. Seryi, JLab

## 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<sub>3</sub>Sn 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)

## 13. The other way round

 Invert the action(s) used to solve the problem (e.g. instead of cooling an object, heat it).
 Make movable parts (or the external environment) fixed, and fixed parts movable.
 Turn the object (or process) "upside down".



## **Cloud and bubble chambers**

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## #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.



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

Unifying physics, 2022, A. Seryi, JLab

## 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.



## **#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.



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 subcritical reactor to generate power or make neutrino factory out of it



## 7. Nested doll

Place one object inside another; place each object, in turn, inside the other.
Make one part pass through a cavity in the other.



## 8. Anti-weight force

- To compensate for the weight of force on an object, merge it with other objects that provide compensating force.
  - To compensate for the weight of force on an object, make it interact with the environment

(e.g. use aerodynamic, hydrodynamic, buoyancy and other forces).



## Wien filter and TRIZ #8 Anti-force

## Wien filter

From Wikipedia, the free encyclopedia

#### Not to be confused with Wiener filter or Wien bridge.

A **Wien filter** also known as **velocity selector** is a device consisting of perpendicular electric and magnetic fields that can be used as a velocity filter for charged particles, for example in electron microscopes and spectrometers. <sup>[1][2]</sup> It is used in accelerator mass spectrometry to select particles based on their speed. The device is composed of orthogonal electric and magnetic fields, such that particles with the correct speed will be unaffected while other particles will be deflected. It is named for Wilhelm Wien who developed it in 1898 for the study of anode rays.<sup>[3][4]</sup> It can be configured as a charged particle energy analyzer, monochromator, or mass spectrometer.<sup>[1][2]</sup>



#### Theory [edit]

Any charged particle in an electric field will feel a force proportional to the charge and field strength such that  $\vec{F} = q\vec{E}$ , where *F* is force, *q* is charge, and *E* is electric field strength. Similarly, any particle moving in a magnetic field will feel a force proportional to the velocity and charge of the particle. The force felt by any particle is then

#### https://en.wikipedia.org/wiki/Wien\_filter

## Since only B acts on spin, can use it for spin manipulation

## **TESLA collider design and TRIZ #8 Anti-force**

- TESLA used head on collisions of e+ and e- beams
- How to separate beams after collisions?
  - Beams are very disrupted after e+e- collision, and cannot propagate down through the incoming apertures

The answer was to use separator with combined E and B field. It does not act on incoming e+ or ebeams, but bends the outgoing beams



## 9. Preliminary anti-action

If it will be necessary to do an action with both harmful and useful effects, this action should be replaced with anti-actions to control harmful effects.
Create beforehand stresses in an object that will oppose known undesirable working stresses later on.



Unifying physics, 2022, A. Seryi, JLab

## **10. Preliminary action**

• Perform, before it is needed, the required change of an object (either fully or partially).

• Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery.





## **Crabbed collisions**

## **11. Beforehand cushioning**

 Prepare emergency means beforehand to compensate for the relatively low reliability of an object.



## **12. Equipotentiality**

• In a potential field, limit position changes (e.g. change operating conditions to eliminate the need to raise or lower objects in a gravity field).



#### Laser cooling

## 14. Spheroidality – Curvature

- Instead of using rectilinear parts, surfaces, or forms, use curvilinear ones; move from flat surfaces to spherical ones; from parts shaped as a cube (parallelepiped) to ball-shaped structures.
  - Use rollers, balls, spirals, domes.
  - Go from linear to rotary motion, use centrifugal forces.



## **Pill-box and crab-cavity**

## **15. Dynamics**

 Allow (or design) the characteristics of an object, external environment, or process to change to be optimal or to find an optimal operating condition.

- Divide an object into parts capable of movement relative to each other.
- If an object (or process) is rigid or inflexible, make it movable or adaptive.



## **Travelling focus**

V. Balakin, 1991

## **16. Partial or excessive actions**

 If 100 percent of an object is hard to achieve using a given solution method then, by using "slightly less" or "slightly more" of the same method, the problem may be considerably easier to solve.



#### Huge coupling due to overlap of solenoid with Final Doublet quads => partial compensation by weak anti-solenoid

Y. Nosochkov, A. Seryi, PRSTAB, 8, 021001 (2005)

Unifying physics, 2022, A. Seryi, JLab

## 18. Mechanical vibration Oscillations and resonances

- Cause an object to oscillate or vibrate.
- Increase its frequency (even up to the ultrasonic from microwave to optical).
  - Use an object's resonant frequency.
  - Use piezoelectric vibrators instead of mechanical ones.
  - Use combined ultrasonic and electromagnetic field oscillations.



## Stochastic cooling => optical stochastic cooling

## 20. Continuity of useful action

Carry on work continuously; make all parts of an object work at full load, all the time.

•

Eliminate all idle or intermittent actions or work.



## Top off injection

## 21. Skipping

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



## 21. Skipping

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



## **Polarization preservation**

• Spin motion in accelerator: spin vector precesses around its guiding field along the vertical direction



- Spin tune Qs: number of precessions in one orbital revolution:  $Qs = \gamma G$ 
  - Anomalous g- factor for proton G= 1.793

Depolarization due to resonances: Imperfection resonances: Qs = nIntrinsic resonances: Qs = nP + Qy

Here n – integer, P – number of superperiods

## **17. Another dimension**

To move into an additional dimension.
 Use a multi-story arrangement of objects instead of a single-story arrangement.
 Tilt or re-orient the object, lay it on its side.
 Use "another side" of a given area.

DNA **Nucleosome** Solenoid Extended Loops of **Metaphase** Double Fiber Section of Chromatin Chromosome Helix (Around Chromosome Fiber **Histones**) (Long Loops on (Tighter Coils) **Non-Histone** 

## **DNA** packaging levels

**Proteins**)
## **Polarization preservation – Siberian snakes**

• Siberian snakes – special (e.g. helical) magnets that rotate spin (preserving orbit outside)



Polarization kinematics of particles in storage rings. Ya.S. Derbenev, A.M. Kondratenko (Novosibirsk, INP) Jun 1973. Zh.Eksp.Teor.Fiz.64:1918-1929,1973

- Full Siberian snakes flip spin 180 degrees. Two full snakes make Qs = 1/2
  - Two full snakes control:
    - Intrinsic resonances
    - Imperfection resonances
- Partial Siberian snake
  - Break coherent build up of perturbation of spin
    - Some control of imperfection resonances

### **Polarization preservation – Siberian snakes**

#### • Siberian snakes in RHIC – two full snake than make $Qs = \frac{1}{2}$





• AGS – partial

SNAKE OH Fmap y =25 — B<sub>x</sub> ---- B<sub>y</sub> ---- B<sub>z</sub> Magnet field in Snake 2 B [tesla] 0 10 12 10 Particle orbit and 5 spin trajectory 0 -5 -10

RHIC snake: 4T, 2.4m/snake, 360° twist, 100mm aperture

First Polarized Proton Collisions at RHIC. T, Roser, et al, AIP Conference Proceedings 667, 1 (2003)

2.6 m



Warm partial AGS Snake

AGS partial snake

# **EIC Hadron Polarization**

- Existing p Polarization in RHIC achieved with "Siberian snakes"
- Near term improvements will increase proton polarization in RHIC from 60% to 80%
- <sup>3</sup>He polarization of >80% measured in source
- 80% polarized <sup>3</sup>He in EIC will be achieved with six "snakes",
- Acceleration of polarized Deuterons in EIC 100% spin transparent
- Need tune jumps in the hadron booster synchrotron



Electron beam ion source EBIS with polarized <sup>3</sup>He extension

#### TRIZ inventive principle #21

#### 21. Skipping

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



Crossing transition energy with  $\gamma_t$  jump technique



*Tune jump for polarization preservation conceptually similar* 

See more examples in "Accelerating Science TRIZ inventive methodology in illustrations" arXiv:1608.00536

"Unifying Physics of Accelerators, Lasers and Plasma" (CRC Press 2015) – in Open Access:

https://doi.org/10.1201/b18696

#### 22. "Blessing in disguise" or "Turn Lemons into Lemonade"

- Use harmful factors (particularly, harmful effects of the environment or surroundings) to achieve a positive effect.
- Eliminate the primary harmful action by adding it to another harmful action
   to receive the problem
  - to resolve the problem.
  - Amplify a harmful factor to such a degree that it is no longer harmful.



#### 23. Feedback

- Introduce feedback (referring back, cross-checking) to improve a process or action.
  - If feedback is already used, change its magnitude or influence.



#### **Stochastic cooling**

#### 24. Intermediary

Use an intermediary carrier object or intermediary process.
Merge one object temporarily with another (which can be easily removed).



#### **Three-level laser**

#### 25. Self service

Make an object serve itself by performing auxiliary helpful functions
 Use waste resources, energy, or substances.



#### 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.



#### 27. Cheap short-living objects

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



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



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

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

#### **Plasma acceleration**

#### **Plasma oscillations**



### **Critical density and surface**

When laser hits a target its surface is heated, and plasma is formed Plasma expands into the vacuum, and its density drops



If  $\omega_p$  is larger than laser frequency  $\omega$ , then the plasma electrons can move fast enough to screen the laser

Therefore, laser penetrates only to the point where  $\omega_p < \omega$ 

$$n_c = \omega^2 / (4\pi c^2 r_e)$$

The critical density is thus



#### How to excite plasma

We see that GeV/cm require plasma with n=10<sup>18</sup> cm<sup>-3</sup>

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

- Thus, short sub-ps pulses needed for plasma excitation
- In absence of short laser pulses other methods suggested:



#### How to excite plasma

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



#### Laser pulse of high intensity

Laser intensity (in vacuum)

$$I = \frac{1}{2} \varepsilon_0 E_{max}^2 c \qquad (SI) \qquad \qquad I = \frac{1}{8\pi} E_{max}^2 c \qquad (Gaussian)$$

Fields in practical units:

$$E_{\max}\left[\left(\frac{V}{cm}\right)\right] \cong 2.75 \times 10^9 \left(\frac{I}{10^{16} W/cm^2}\right)^{1/2} \qquad B_{\max}\left[Gauss\right] \cong 9.2 \times 10^6 \left(\frac{I}{10^{16} W/cm^2}\right)^{1/2}$$

(useful to remember that 300 V/cm is ~same as 1 Gauss)

Compare with field in a hydrogen atom. Bohr radius and field:

$$a_{B} = \frac{\hbar^{2}}{me^{2}} = 5.3 \times 10^{-9} \text{ cm} \qquad E_{a} = \frac{e}{a_{B}^{2}} \qquad = \frac{e}{4\pi\epsilon_{0}a_{B}^{2}} \approx 5.1 \times 10^{11} \frac{\text{V}}{\text{m}}$$
(Gaussian) (SI)
(Recall  $\epsilon_{0} \approx 8.8 \cdot 10^{-12} \frac{\text{A}^{2} \cdot \text{s}^{4}}{\text{kg} \cdot \text{m}^{3}}$ )
Atomic intensity  $I_{a} = \frac{\epsilon_{0}cE_{a}^{2}}{2} \cong 3.51 \times 10^{16} \frac{\text{W}}{\text{cm}^{2}}$ 

A laser with intensity higher than that will ionize gas immediately

### Laser intensity



## **Types of ionization**



### Laser intensity for barrier suppression ionization



Coulomb potential of hydrogen atom distorted by homogeneous field  $\epsilon$ :  $V(x) = -\frac{e^2}{-e\epsilon x}$ 

> Find position of the maximum:  $x_{max} = (e / \epsilon)^{1/2}$

X

Equate potential value at max to hydrogen ionization potential

$$V(x_{max}) = 2(e^{3}\varepsilon)^{1/2} = E_{ion} = \frac{e^{2}}{2a_{B}} \approx 13.6eV$$

 $\varepsilon_{\rm c} = \frac{{\rm e}}{16a_{\rm p}^2} = \frac{{\rm E}_{\rm a}}{16}$ 

The critical field for hydrogen is therefore

Which corresponds to intensity  $I_c = \frac{I_a}{256} \approx 1.4 \cdot 10^{14} \, \text{W} \, / \, \text{cm}^2$ 

### Laser intensity



#### **Normalized vector potential**

The laser field can be written in terms of the vector potential of the laser field A as

For linearly polarized field

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{c\partial t}, \quad \mathbf{B} = \nabla \times \mathbf{A}$$
$$\mathbf{A} = \mathbf{A}_0 \cos(\mathbf{k} \mathbf{z} - \omega t) \mathbf{e}_{\perp}$$

We see that 
$$E_0 = \frac{A_0\omega}{c}$$

Compare momentum gained by e- in one cycle of laser field

$$\Delta t \cong \frac{eE}{\omega}$$
 with

with 
$$m_e^{C}$$

We see that it is useful to define the normalized vector potential as

$$\mathbf{a} = \frac{e\mathbf{A}}{m_e c^2}$$
 with amplitude  $a_0 = \frac{eE_0}{m_e \omega c}$ 

The amplitude  $a_0$  will indicate if the electron motion in laser field relativistic  $a_0 >> 1 -$  relativistic,  $a_0 << 1 -$  non relativistic

eЕ

$$\begin{array}{ll} \mbox{In practical} \\ \mbox{units} \end{array} & a_0 \approx \left( \frac{I \left[ W \, / \, cm^2 \right]}{1.37 \cdot 10^{18}} \right)^{\frac{1}{2}} \cdot \lambda [\mu m] \end{array} \qquad \mbox{where} \qquad \lambda = \frac{2\pi c}{\omega}$$

### **Laser intensity**



#### **Laser acceleration - conceptually**



- Note in particular
  - Ionization front starting at the front tail of laser
  - Laser pulse length similar of shorter than plasma wavelength
  - Electrons trapped in the first bubble

#### Formation of bubble – ponderomotive force

First, assume laser field homogeneous:  $E = E_0 \cos(\omega t)$ 

Motion of electron: 
$$\ddot{y} = \frac{F}{m} = \frac{eE}{m} \implies y = -\frac{eE_0}{m\omega^2} \cos(\omega t)$$
  
Now, assume E has  
gradient in y:  $E = E_0(y)\cos(\omega t) \approx E_0\cos(\omega t) + y\frac{\partial E_0}{\partial y}\cos(\omega t)$   
Find time average of  
force acting on e-:  $\langle F \rangle_t = \left\langle -\frac{eE_0}{m\omega^2}\cos(\omega t) \cdot \frac{\partial E_0}{\partial y}\cos(\omega t) \right\rangle_t$   
**y** Laser  
 $\left\langle F \rangle_t = -\frac{e^2}{2m\omega^2}E_0\frac{\partial E_0}{\partial y} = -\frac{e^2}{4m\omega^2}\frac{\partial E_0^2}{\partial y}$   
 $F_p$   
Ponderomotive force pushes electrons  
out from the high intensity region

### **Laser-Driven Plasma Acceleration**



- Ponderomotive force of short (50fs), intense (10<sup>18</sup> W cm<sup>-2</sup>) 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



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)
  - Methods which involve two laser pulses and mix of two gases with different ionization potential

### 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

## First ever 1 GeV from laser plasma accelerator

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



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

Plasma density 2.7x10<sup>18</sup> cm<sup>-3</sup>, 40 TW laser with 1018 W/cm<sup>2</sup>

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



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

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

#### **Transverse fields in the bubble**



The ions are heavy and are inside of the bubble. They produce focusing force.

$$\oint \mathbf{E} \cdot d\mathbf{S} = 4\pi \int \rho dV$$
 (Gaussian)

Assume cylindrical symmetry

Focusing force

$$eE = 2\pi ne^2 r$$

Assume electron is relativistic with  $\gamma$ It will oscillate in this field as

$$\frac{\mathrm{d}^2 \mathrm{r}}{\mathrm{ds}^2} = \frac{2\pi \mathrm{ne}^2 \mathrm{r}}{\gamma \mathrm{mc}^2} = \frac{\omega_\mathrm{p}^2}{2\gamma \mathrm{c}^2} \mathrm{r}$$

The period of oscillation is therefore  $\lambda = \sqrt{2\gamma} \lambda_p$ 

### **Betatron radiation**



- Strong radial electric field within plasma wave cause transverse oscillation of electron bunch
- Generates bright betatron radiation in 1-100 keV range
- Let's estimate parameters of this radiation

### **Betatron radiation**



- Strong radial electric field within plasma wave cause transverse oscillation of electron bunch
- Generates bright betatron radiation in 1-100 keV range
- Let's estimate parameters of this radiation

#### Synchrotron radiation on-the-back-of-theenvelope – power loss

Energy in the field left behind (radiated !):



#### Synchrotron radiation on-the-back-of-theenvelope –photon energy


## Synchrotron radiation on-the-back-of-theenvelope –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  $\theta$ :  $N \approx \alpha \gamma \theta$ )

Gaussian units on this page!

## **Estimations of betatron radiation**

	We found that relativistic electron with $\gamma$ will oscillate in the field of ions as
,,,_,_,,_,_,_,_,_,_,_,_,_,_,_,_	$\frac{d^{2}r}{ds^{2}} = \frac{2\pi ne^{2}r}{\gamma mc^{2}} = \frac{\omega_{p}^{2}}{2\gamma c^{2}}r$ period of oscillation is $\lambda = \sqrt{2\gamma} \lambda_{p}$
	If amplitude of oscillation is $r_b$ then the radius of curvature of the trajectory is $R = \frac{\lambda^2}{4\pi^2 r_b}$
Substitute and get the	radius of curvature as $R = \frac{\gamma \kappa_p}{2\pi^2 r_b}$
Substitute into $\omega_{c} = \frac{3}{2} \frac{c \gamma^{3}}{R}$ and get estimates and radiation v	stimation of vavelength $\lambda_{c} = \frac{\lambda_{p}^{2}}{3\pi\gamma^{2}r_{b}}$
Use $\frac{dN}{dS} \approx \frac{\alpha \gamma}{R}$ to estimate $N_{\gamma}$ pho emitted per $\lambda$	tons $N_{\gamma} \approx \sqrt{2\gamma} \ 2\pi^2 \alpha \frac{r_b}{\lambda_p}$
Assume 1GeV ( $\gamma$ =2E3), $\lambda_p$ =0.03mm, $r_b$ =0	$001 \text{ mm} \Rightarrow \lambda_c = 0.25 \text{ A or } \sim 50 \text{ keV} \qquad \text{Many hard} \\ \text{and } N_\gamma \text{ per } \lambda \text{ is } \sim 0.3 \qquad \text{photons!}$

#### **19. Periodic action**

Instead of continuous action, use periodic or pulsating actions.
If an action is already periodic, change the periodic magnitude or frequency.
Use pauses between impulses to perform a different action.



#### **Devices for generation of synchrotron radiation**



# **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 <a href="https://www.nature.com/articles/s41586-021-03678-x">https://www.nature.com/articles/s41586-021-03678-x</a>

"experimental evidence of FEL lasing by a compact (3-cm) particle-beamdriven 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



#### 28. Mechanics substitution

- Replace a mechanical means with a sensory (optical, acoustic, taste or smell) means.
- Use electric, magnetic and electromagnetic fields to interact with the object.
- Change from static to movable fields, from unstructured fields to those having

#### structure.

• Use fields in conjunction with field-activated (e.g. ferromagnetic) particles.



#### **29.Pneumatics and hydraulics**

Use gas and liquid parts of an object instead of solid parts (e.g. inflatable, filled • with liquids, air cushion, hydrostatic, hydro-reactive).



#### 30. Flexible shells and thin films

• Use flexible shells and thin films instead of three dimensional structures Isolate the object from the external environment using flexible shells and thin films.



#### Light sail laser-plasma ion acceleration

#### **31. Porous materials**

Make an object porous or add porous elements (inserts, coatings, etc.). If an object is already porous, use the pores to introduce a useful substance or function.

#### Membranes made with ion beams



Illustration from "Engines of Discovery: A Century of Particle Accelerators", A. Sessler and T. Wilson, 2007.

#### 32. Color changes

• Change the color of an object or its external environment.

• Change the transparency of an object or its external environment.

- To improve observability of things that are difficult to see, use colored additives or
   luminescent elements.
  - Change the emissivity properties of an object subject to radiant heating.



**Optical Parametric Chirped Pulse Amplification - OPCPA** 

#### 33. Homogeneity (Similia similibus curantur)

• Make objects interacting with a given object of the same material (or material with identical properties).



#### **Electron cooling**

## The need for beam cooling – IBS

 Intrabeam Scattering (IBS): Lorentz boosted Coulomb scattering inside bunches



- Higher charge and smaller emittances increase IBS growth rate
  - IBS can be partially mitigated by reducing dispersion and increasing energy spread
- IBS rates for EIC parameters ~2 hour
- Beam cooling methods needed to counteract IBS



Cooling gets much weaker at higher energy

Cooling gets much weaker for denser bunch

- Either of these methods, if scaled to EIC parameters and stay within technically feasible range, will not provide sufficient cooling they would be too weak
- For EIC "Strong" hadron cooling is needed cooling that will provide sufficiently high cooling rate for proton bunches at EIC parameters

## **Electron Cooling**



**Electron cooling concept** 

When electron cooling idea was first presented (1966), the common opinion of the community was – "brilliant idea, but unfortunately non-realistic"



Budker G.I., Effective method of damping particle oscillations at proton antiproton storage rings, Atomic Energy 1967, v.22, №5, p.346



First e-cooler at INP, Novosibirsk, ~1974

## **Magnetized Electron Cooling**

Initial measurements at INP show cooling time of 17 s (protons, 65 MeV) There was expectation that protons will cool to equilibrium temperature of 1000K (cathode temperature)

$$\frac{MV_i^2}{2} = \frac{mV_e^2}{2} = T_{equilibrium}$$

However, after alignment improvement of the magnetic system, the cooling time became 0.05 s, consistent with electron beam temperature 1K

Reasons:

1) Longitudinal T of electrons flattens due to acceleration:

2) Transverse T of electrons does not play any role if Larmor radius << n<sup>-1/3</sup>



The magnetization effects in electron cooling, Ya. Derbenev, A. Skrinsky, Rus. Plasma Physics, v.4 (1978) 492

 $T_{\parallel} = \frac{T_{Cathode}}{R^2 w^2 m a^2}$ 

They called it

*"fast electron* 

cooling"

## **Single Pass Electron Cooling Experiment**



Magnetization effects allowed to observe the difference of the e-cooling friction force (which is normally  $\sim e^2Z^2$ ) on the charge of the particle





## Experiment at MOSOL revealed large difference in cooling force for positive and negative particles

Reason: in magnetized case and low relative velocity, the negative ion reflects the electron, making a large momentum transfer, while for positive ion the electron is first attracted and then pulled back, minimizing momentum transfer



# **Electron Cooling & Energy Recovery**



Typical scheme of a standard electron cooler for low energy range (~several tens MeV of p energy)

- Standard electron cooling use energy recovery
  - For example, if we need 1A @ 1MeV electron beam\*, it does not mean we need 1 MW power supply
- Typical arrangements of e-cooler power supplies:



- Losses of 1A e-beam due to interaction with p-beam or scattering are low
- Thus, power of 1MV power supply is defined by e-beam losses and can be much lower than 1MW, just 1kW in example above

\* Numbers are for illustration only

# **Taking Electron Colling to higher energy**

• Energy recovery is even more important for high energy electron cooling



- The electron cooling time has a very unfavourable beam energy scaling  $\sim \gamma^{2.5}$
- Mitigating scaling dependence by a) increasing cooling section length; b) higher electron current – has practical limits
- For 41-257 GeV energy of EIC proton beam standard electron cooling would be extremely challenging

# **Getting electron cooling to higher energy**

#### Low-Energy RHIC electron Cooler (LEReC) at BNL:

(100 meters of beamlines with the DC Gun, high-power fiber laser, 5 RF

- First e-cooler based on the RF acceleration of e-beam (of up to 2.6 MeV energy)
- Observation of first cooling using bunched electron beam on April 5, 2019
- LEReC will be used in RHIC Beam Energy Scan II for Low energy ( $\sqrt{s_{NN}} = 7.7, 9.1, 11.5, 14.5, 19.6 \text{ GeV}$ ) Au+Au runs using electron cooling to increase luminosity
- Cooling using bunched electron beam produced with RF acceleration is new, and opens the possibility of electron cooling at high beam energies





LEReC approach can be used for EIC as injection energy pre-cooler. However, at collision energy enhanced/strong cooling mechanism is needed.

#### 34. Discarding and recovering

- Make portions of an object that have fulfilled their functions go away (discard by dissolving, evaporating, etc.) or modify these directly during operation.
  - Conversely, restore consumable parts of an object directly in operation.



#### **Semiconductor Saturable Absorber Mirror - SESAM**

#### **35. Parameter changes**

Change an object's physical state (e.g. to a gas, liquid, or solid.)

- Change the concentration or consistency.
  - Change the degree of flexibility.
    - Change the temperature.















and fibre lasers	
a	re <u>connected via</u> <u>TRIZ inventive</u> <u>principles!</u>

#### 36. Phase transitions

• Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).



#### 37. Thermal or electrical expansion or property change

- Use thermal or electrical expansion (or contraction) or other property change of materials.
- If thermal or electrical expansion (property change) is being used, use multiple materials with different coefficients of thermal expansion (property change).



Electro-optic effect dependence of optical properties of objects such as absorption or refraction (Pockels effect) on the applied electric field

#### 38. Strong oxidants

- Replace common air with oxygen-enriched air.
  - Replace enriched air with pure oxygen.
  - Expose air or oxygen to ionizing radiation.
    Use ionized oxygen.
- Replace ozonized (or ionized) oxygen with ozone.



#### **TITANSCAN\*** SURεβEAM TECHNOLOGY Electronic Pasteurization System Sioux City, Iowa

## Irradiation of food for sterilisation

**Illustration: TITANSCAN** 

#### 39. Inert atmosphere

- Replace a normal environment with an inert one.
- Add neutral parts, or inert additives to an object.



Sulfur hexafluoride (SF6 or Elegas) is a colorless nonflammable gas with excellent electric insulating and arcquenching capacity. It is widely used in the fields of electric, laser, medical, meteorological, freezing, fire-fighting, chemical, military, space aviation, nonferrous metallurgy and physical research areas.

#### 40. Composite materials

• Change from uniform to composite (multiple) materials.

## Ion beam surface treatment Hardening an artificial knee joint using ion implantation



Illustration from "Engines of Discovery: A Century of Particle Accelerators" A. Sessler and T. Wilson, 2007



"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

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  - <u>https://www.unifyingphysics.com/</u>
- CERN for "eBook for all!" program that enabled conversion of the 1<sup>st</sup> edition of "Unifying Physics…" to open access











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# Slides are available at

### - https://www.unifyingphysics.com/



## – See section Resources

 You can also access the 1<sup>st</sup> edition of the book which is now Open Access

# Thank you for your attention!

# And thanks to all colleagues for materials used in these slides