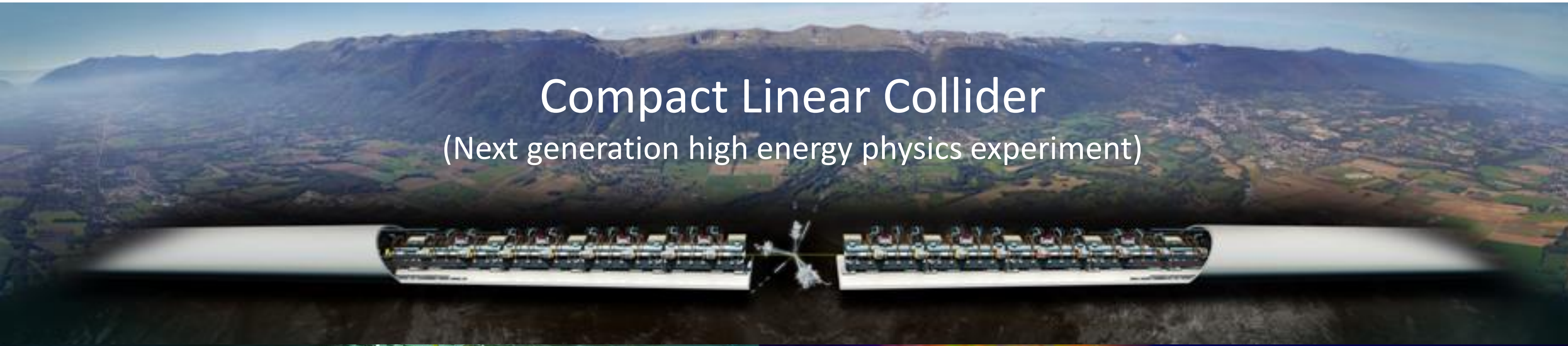
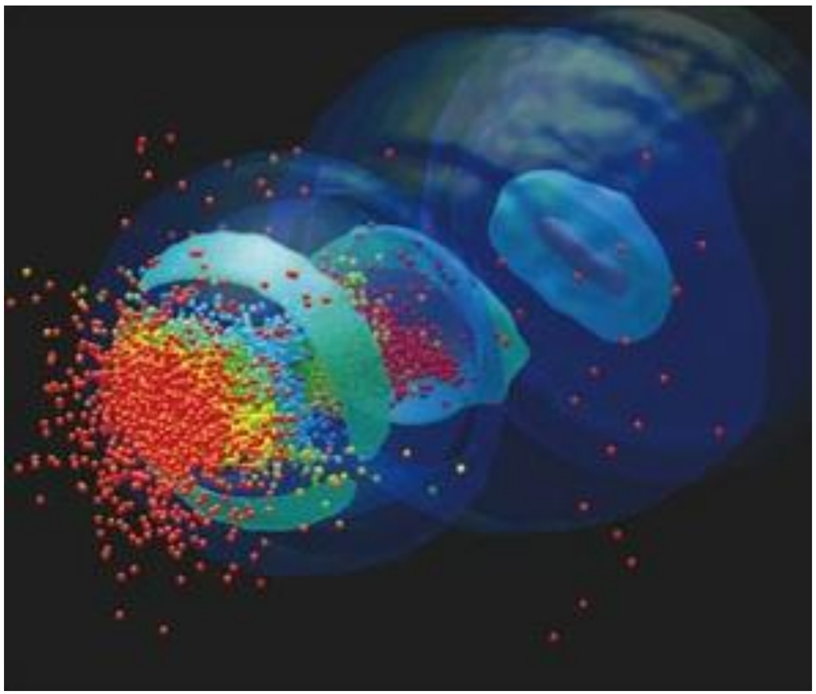
Accelerator R&D at the Univ. of Oslo



Content



1. Introduction to particle accelerator science.

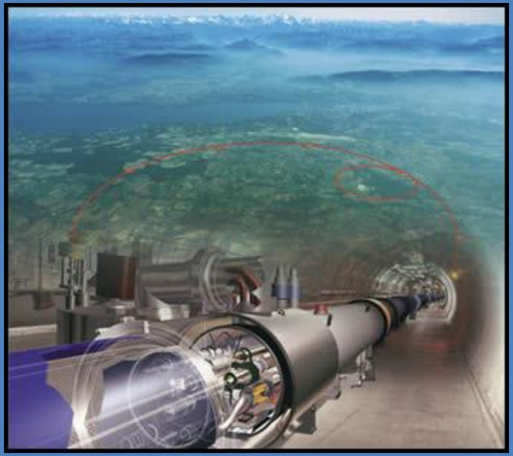
1. R&D program at the UiO.
   - The Compact Linear Collider.
   - Wakefield acceleration.
   - European Spallation Source.
   - Hadron therapy.
   - Free-Electron Lasers.

1. Summary

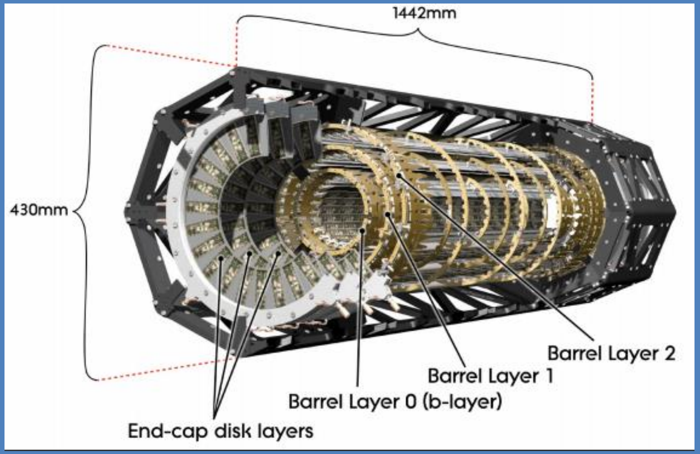
1. Introduction to particle accelerator science

High energy physics at CERN

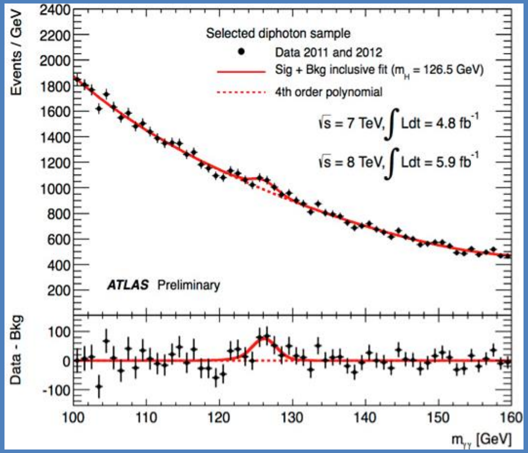
Particle accelerator physics



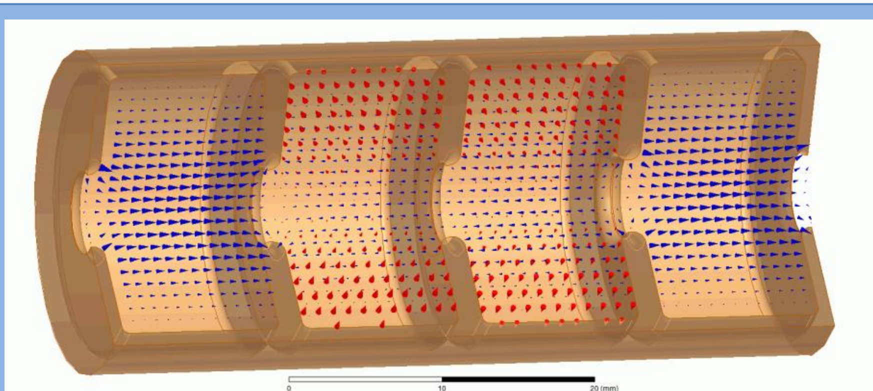
Particle detectors



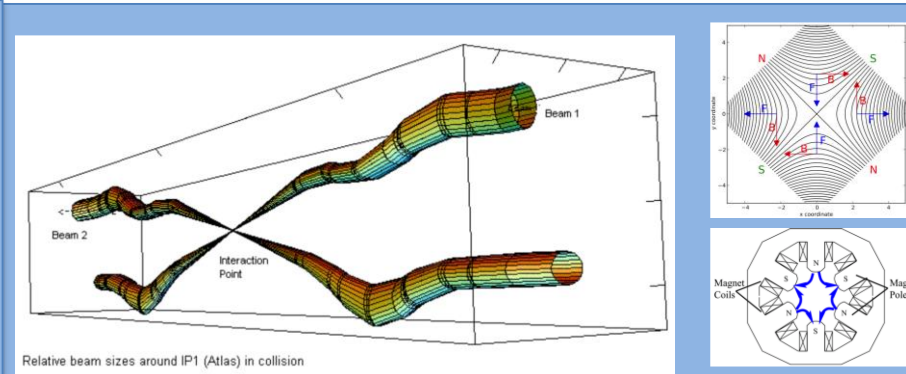
Data analysis



Core elements of accelerator physics

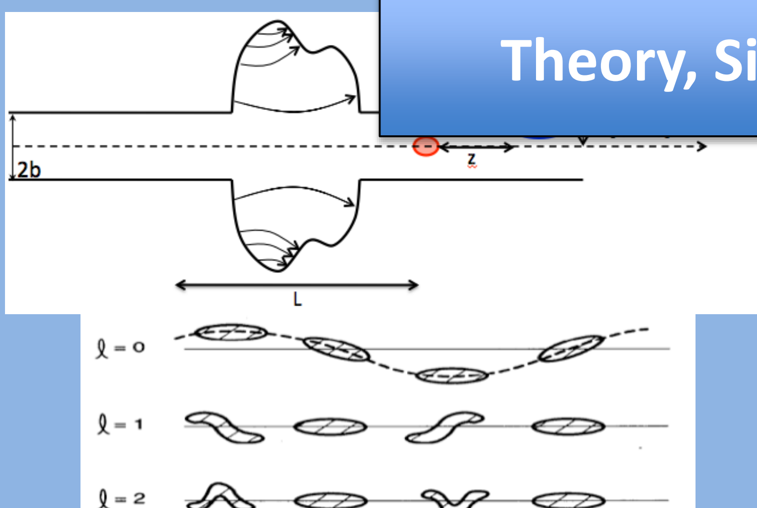


Radio-frequency technology

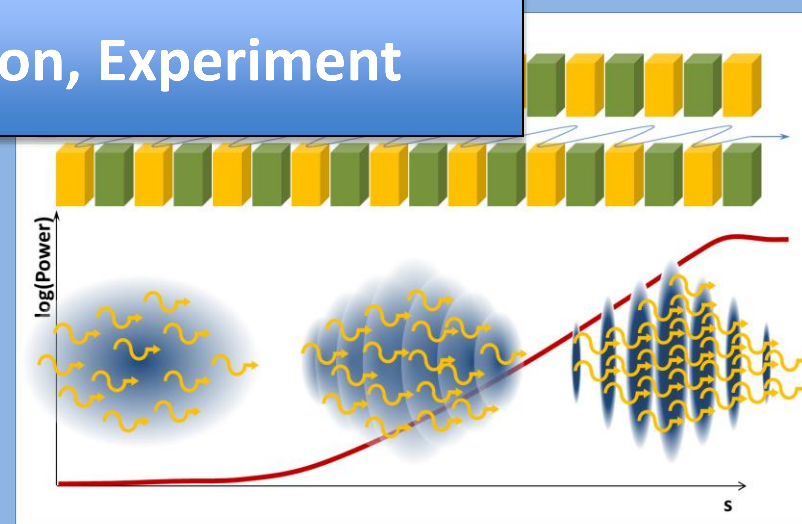


Charged particle beam non-linear optics

Theory, Simulation, Experiment



Collective effects and beam instabilities



Radiation generation

Norwegian accelerator physicists

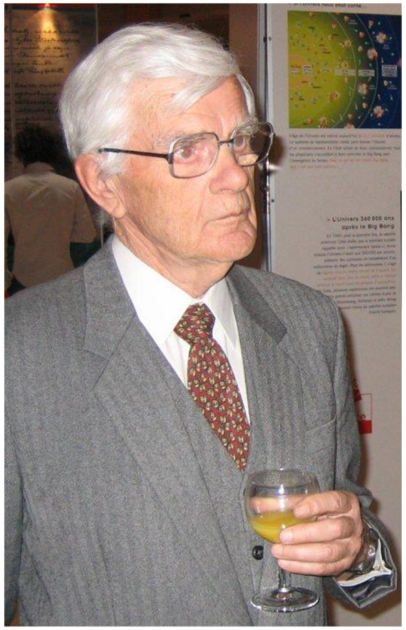
Norway has a proud **tradition** of international particle accelerator physics expertise.

Rolf Wideröe

Oppfinneren radio-frekvensbasert akseleratorer

Odd Dahl

Leder av CERN PS prosjektet (en viktig del av LHC-komplekset den dag i dag)



Kjell Johnsen

Leder av CERN ISR, og leder av CERN's gruppe for akseleratorforskning

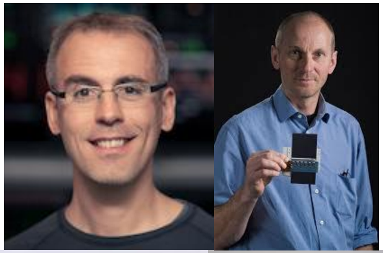
Bjørn Wiik

Professor og direktør ved Europas nest største akseleratorsenter (DESY i Hamburg)

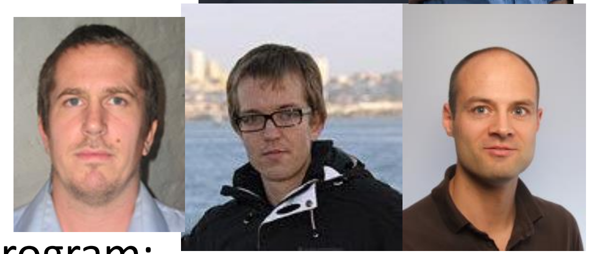
However, until now we have not had any significant local national competence.

Accelerator science at UiO

- 2 professors
  - Erik Adli (erik.adli@fys.uio.no, particle accelerator project leader)
  - Steiner Stapnes (CERN LC study leader)



- 3 Post.Docs:
  - Reidar Lillestol
  - Juergen Pfingstner
  - Håvard Gjersdal



- 4 Ph.D. students funded by UiO or CERN Ph.D. student program:
  - Riccard Andersson
  - Carl Lindstrøm
  - Lukas Malina
  - Veronica Olsen

- 1 M.Sc. student
  - Rune Sivertsen

Projects overview

Linear colliders for HEP, CLIC

Reidar Lillestøl
Lukas Malina

Plasma wakefield acceleration – FACET@SLAC and AWAKE@CERN

Veronica K.B.Olsen
Rune Sivertsen

Carl A. Lindstrøm

Juergen Pfingstner

Medical accelerators
Compact accelerators for particle therapy (based on CLIC technology)

Free electron lasers
Compact FELs (based on CLIC technology).
Opportunity for Norway?

Erik Adli

Project leader for particle accelerator based activities.

ESS and proton-drivers

Riccard Andersson

ESS Norwegian in-kind contribution

Håvard Gjersdal
Ole Røhne (25%)
Maja Olvegård – Uppsala cooperation

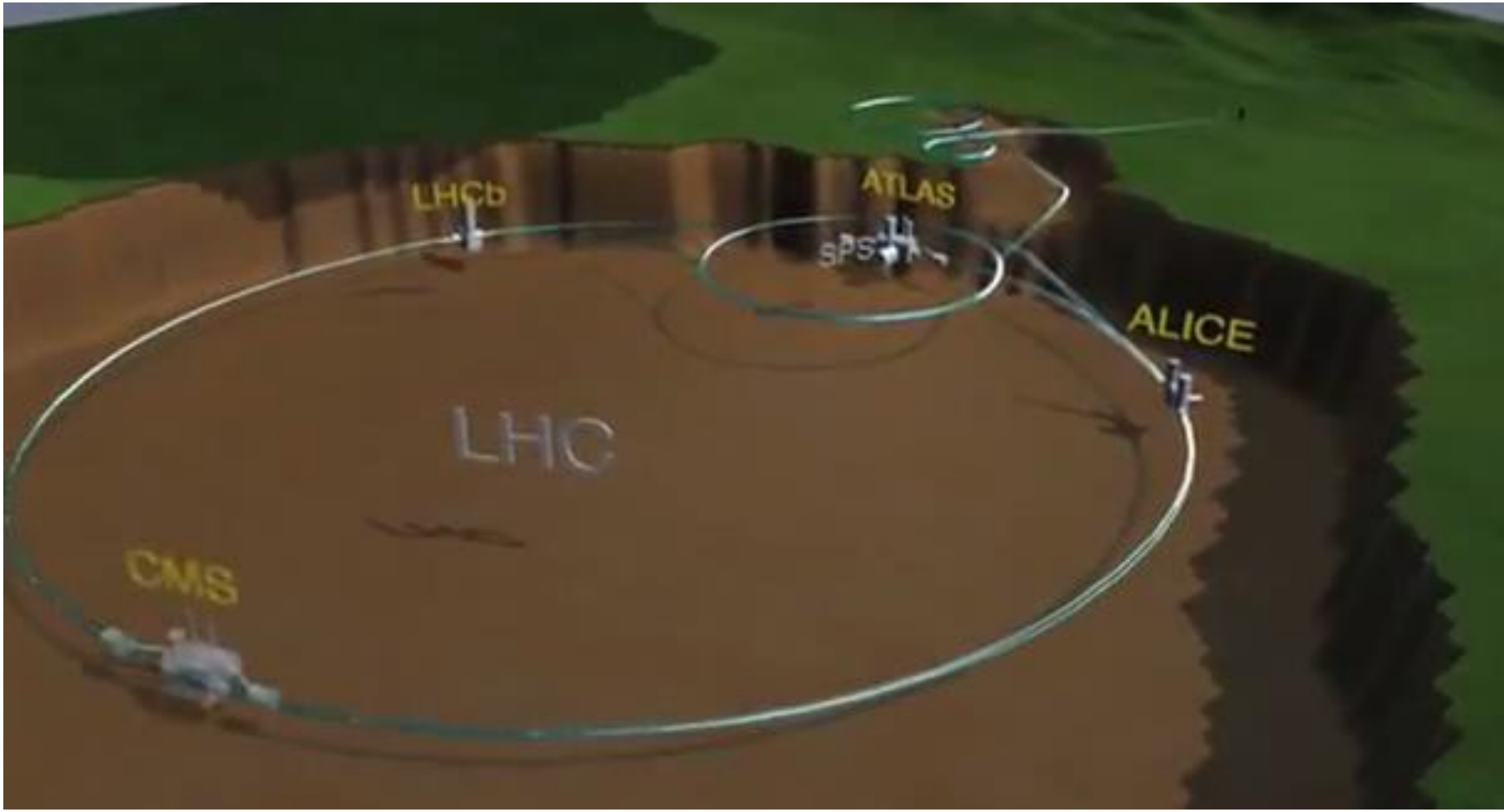
Others (*Lukas Malina*, LHC operations)

2. R&D program at the University of Oslo

2.1 Future high energy accelerators

Compact Linear Collider

The Large Hadron Collider

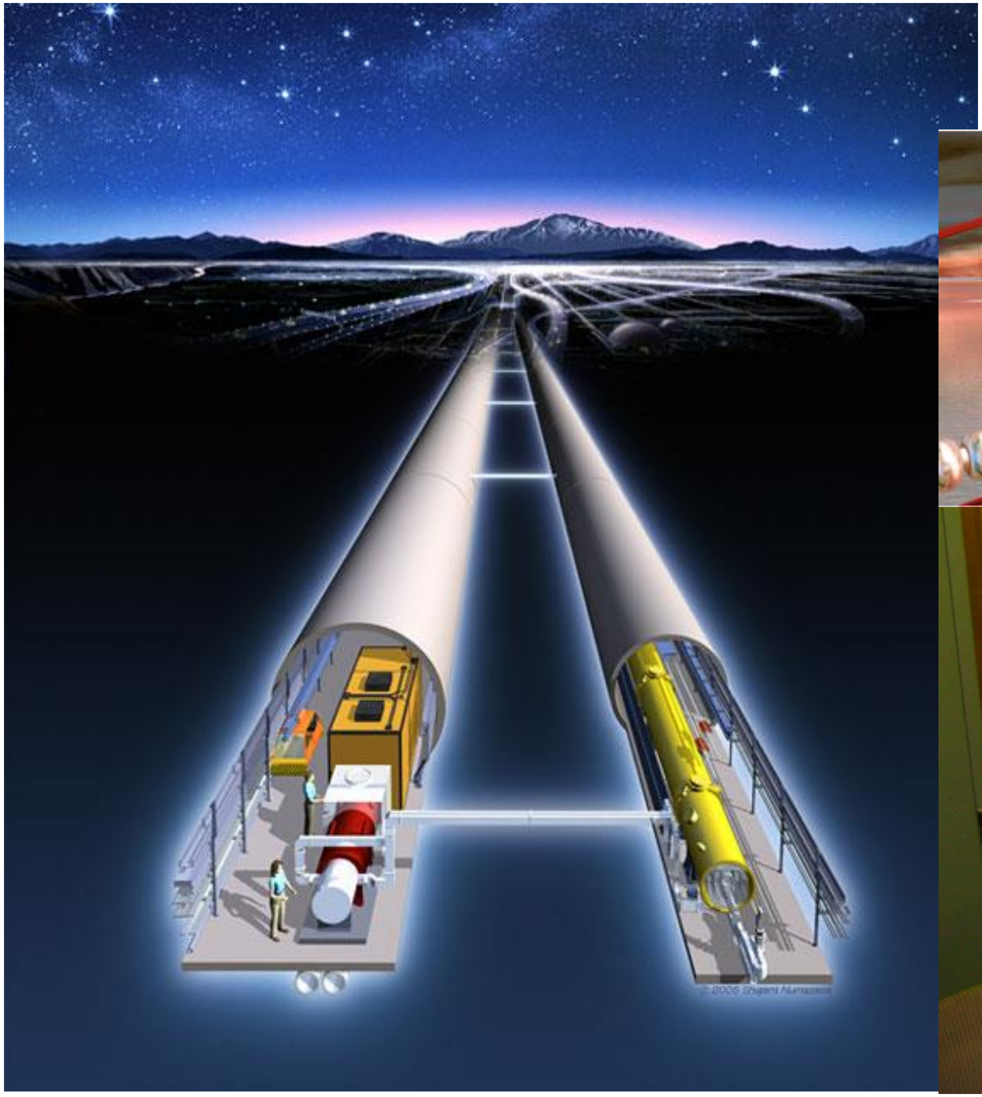


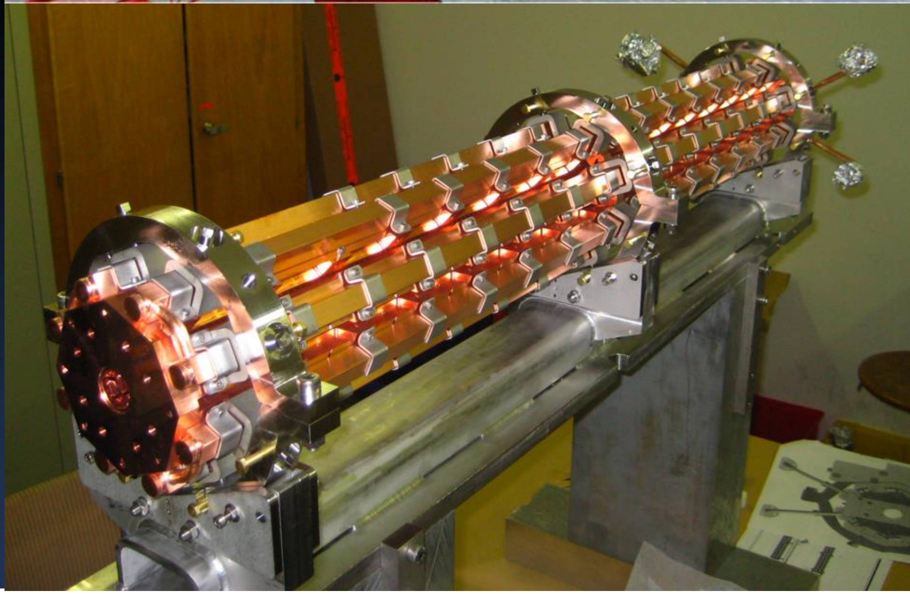
[youtube: the LHC Accelerator]

Future colliders for HEP

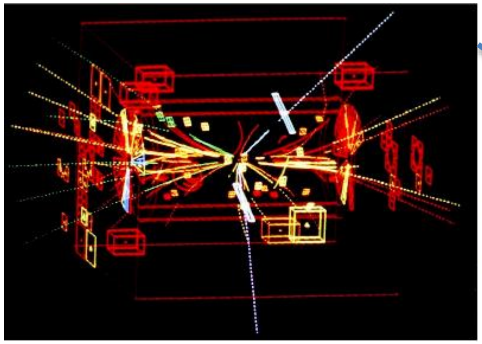
The next big thing?

Maybe a Linear Collider of several 10 km. Why? And How?

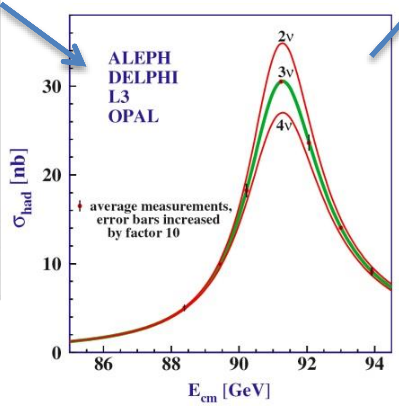




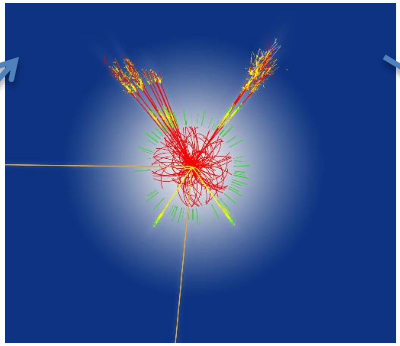
Hadron versus lepton colliders



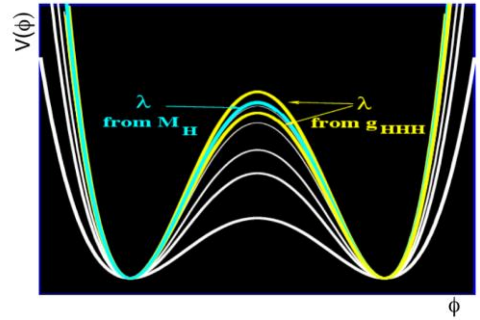
Hadron collider **SppS**,
$\sqrt{s}$=540 GeV,
$W^{+/-}$ and Z^0 discovery
[1983]



e- e+ collider, **LEP,**
$\sqrt{s}_{max}$=209 GeV,
precision measurements of
Z^0 decay width
[1989-2000]

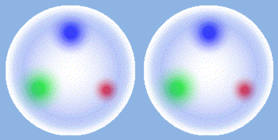


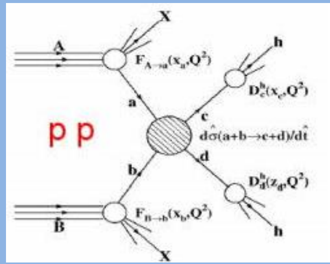
pp collider, **LHC,**
$\sqrt{s}_{max}$=14 TeV,
Higgs discovery
[2008->]



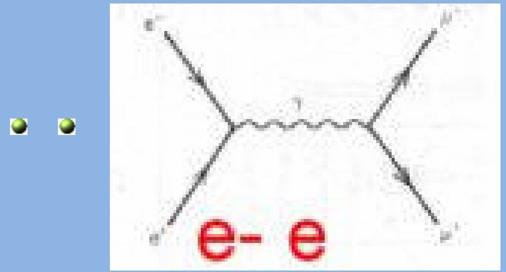
Future:
TeV e- e+ collider,
Precision physics,
Model independent
measurements
Must be linear!

Hadron collisions





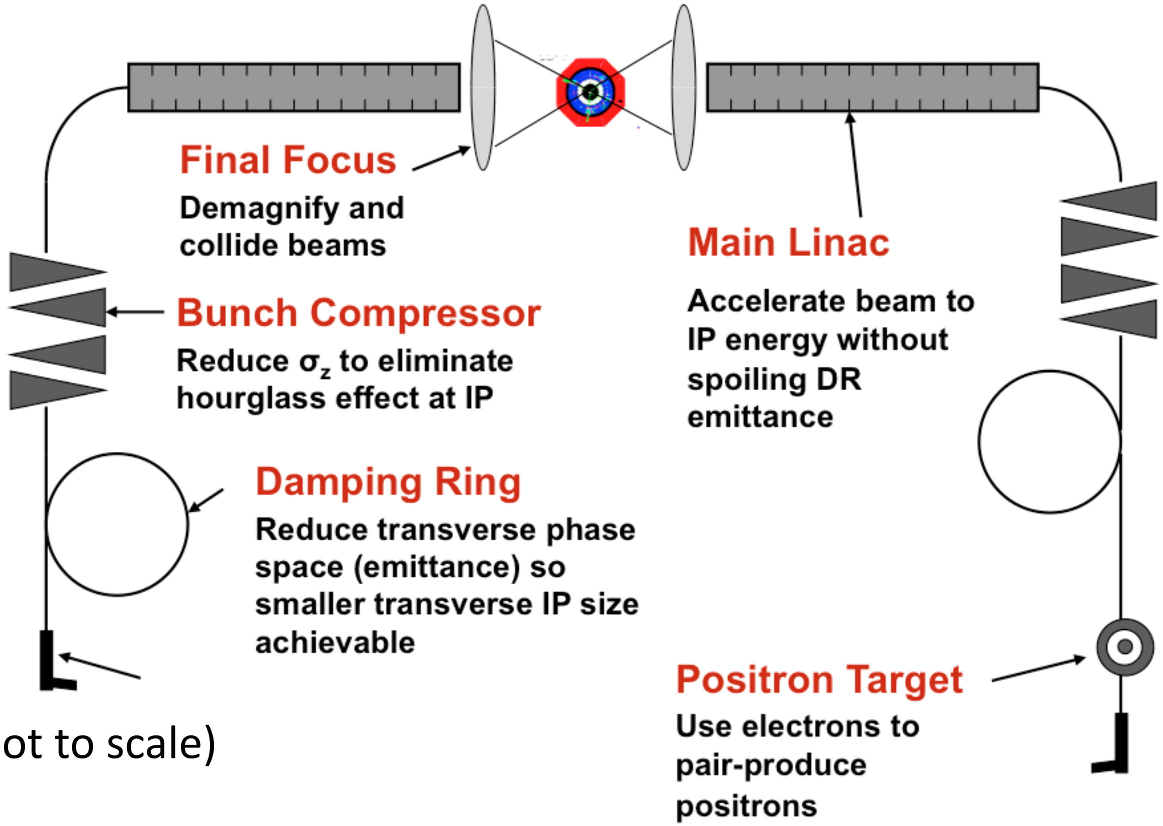
Lepton collisions



Synchrotron radiation

$$P = \frac{e^2 c}{6\pi\varepsilon_0} \frac{1}{(m_0 c^2)^4} \frac{E^4}{R^2}$$

Linear Collider Challenges



(Not to scale)

Design challenge :
Collide as many **particles per second per area**, as possible - at **as high collision energy** as possible – in a cost and **energy effective** manner.

Key requirements :

- High accelerating fields (limited to ~100 MV/m)
- Good energy efficiency (5-10% from wall-plug to beam)
- Excellent beam quality (small emittance, low energy spread)

World Wide Linear Collider Collaborations

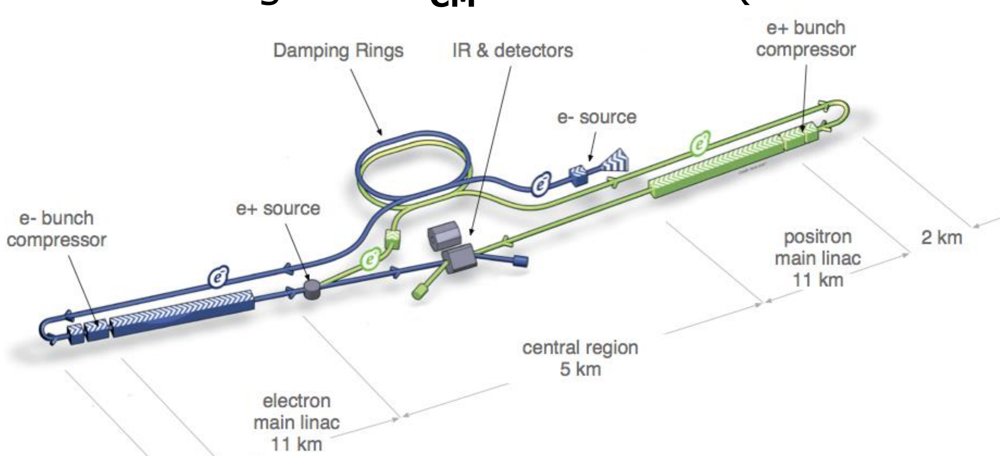
The Compact Linear Collider, CLIC

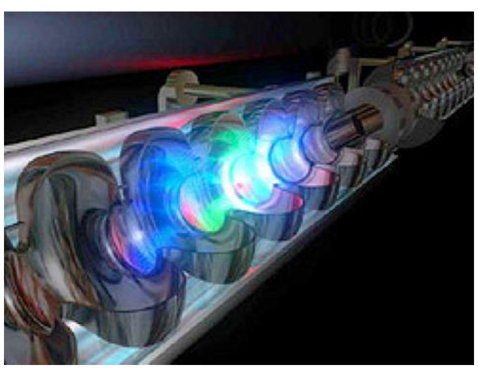
Main linac technology: normal conducting 12 Ghz cavities, **acc. field = 100 MV/m**
Nominal design for **E_{CM} = 3 TeV** (375 GeV to 3 TeV). **50 km at 3 TeV c.o.m**.

Compact Linear Collider

The International Linear Collider, ILC

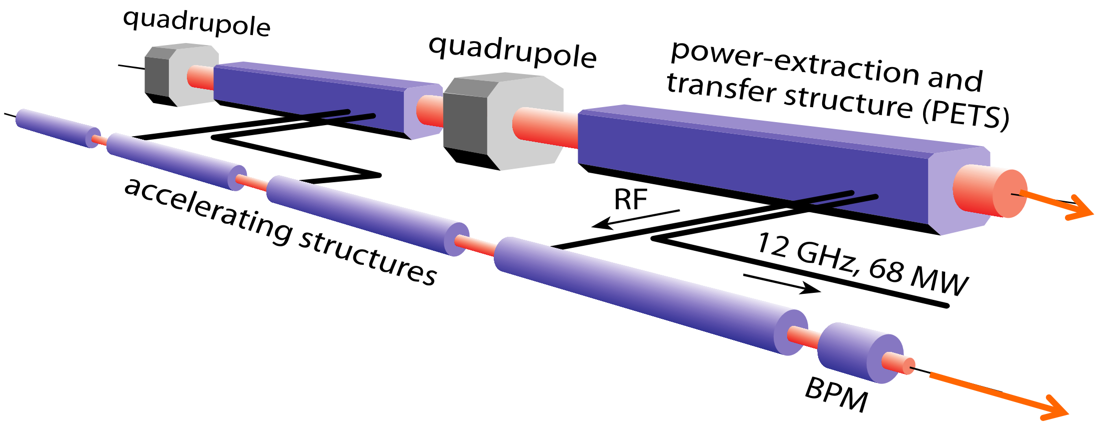
Main linac technology: super conducting 1.3 GHz cavities, **acc. field = 31.5 MV/m**
Nominal design for **E_{CM} = 0.5 TeV** (250 GeV to 1 TeV). **30 km at 0.5 TeV c.o.m**.



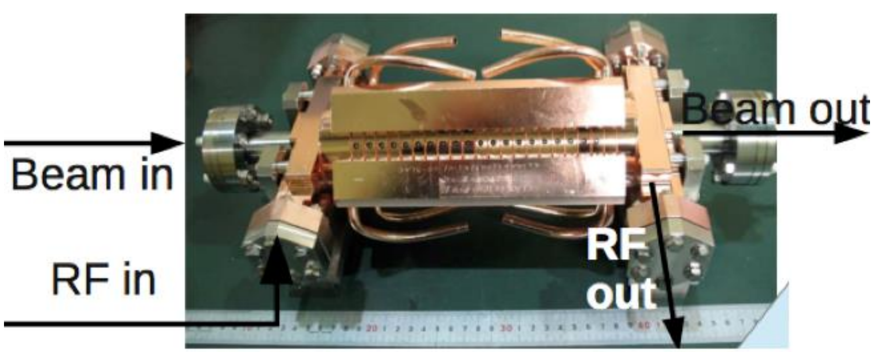


The CLIC Two-Beam scheme

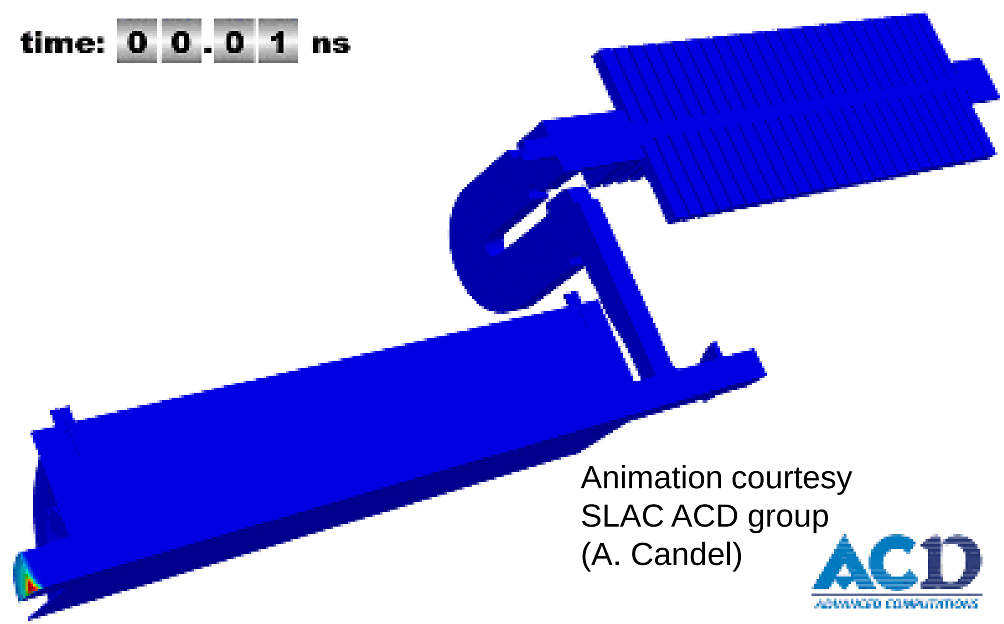
Key concept in CLIC to achieve **100 MV/m** in an power efficient manner: **two-beam acceleration.**



1. Drive beam - **101 A**, 2.4 GeV.
2. Main beam – 1 A, 9 GeV to **1.5 TeV.**

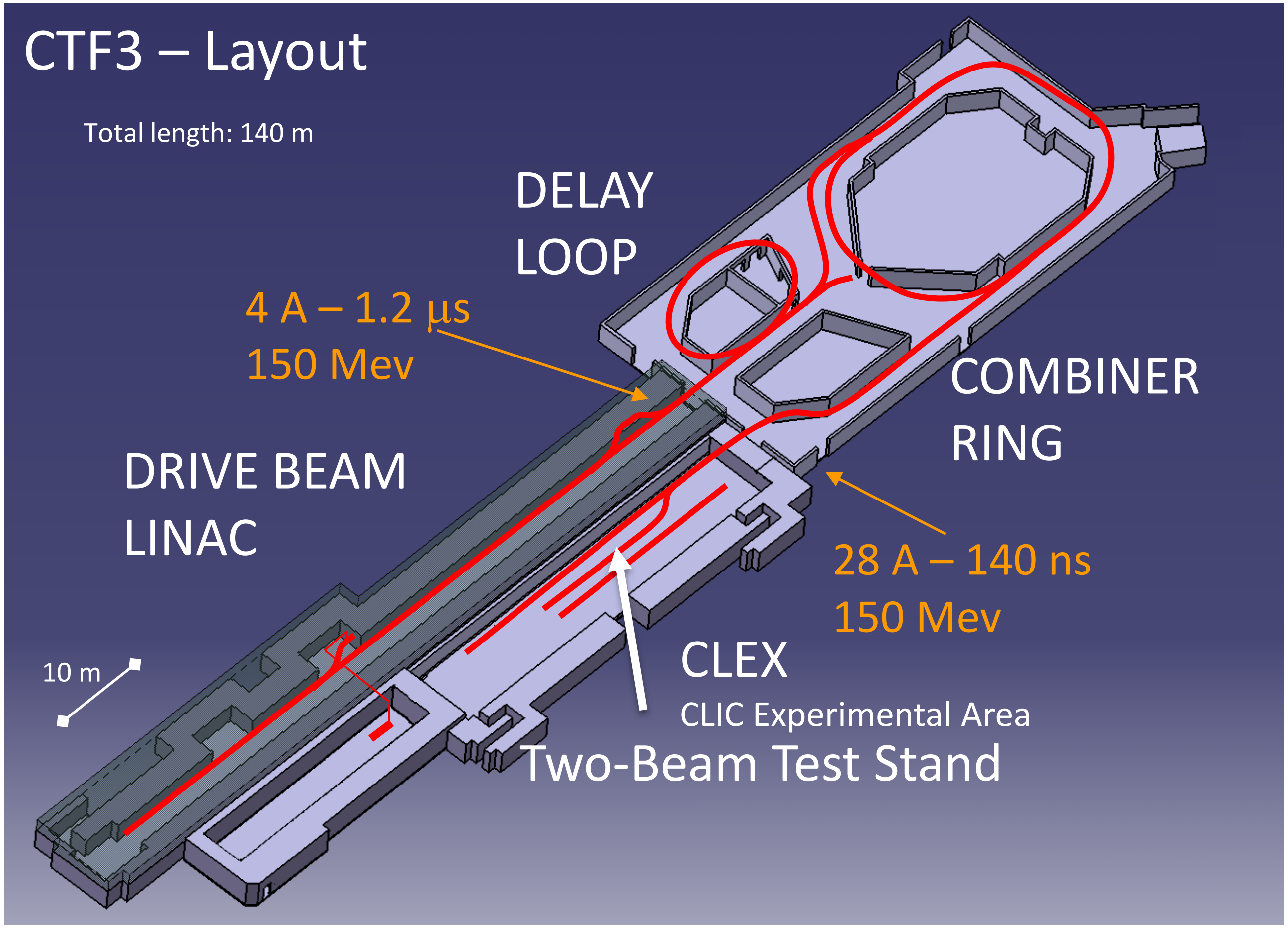


CLIC 100 MV/m accelerating structure. (20 cm long)



Animation courtesy SLAC ACD group (A. Candel)

The CLIC Test Facility 3 at CERN



CLIC Test Facility 3 : designed to **experimentally verify** key concept of the two-beam scheme.

- ***Drive Beam generation***: acceleration in a fully loaded linac with 95 % efficiency and bunch **frequency multiplication** by a factor x 2 x 4 (from 1.5 GHz to 12 GHz)
- ***Two-Beam Acceleration* experiment – reach nominal CLIC gradient and pulse length**
- ***Deceleration* experiment** – heavy deceleration of intense electron beam (>50 %)

Two-beam acceleration experiments

The Oslo group is heavily involved in the experimental verification of the two-beam acceleration scheme at CERN, in cooperation with CERN and Uppsala University.

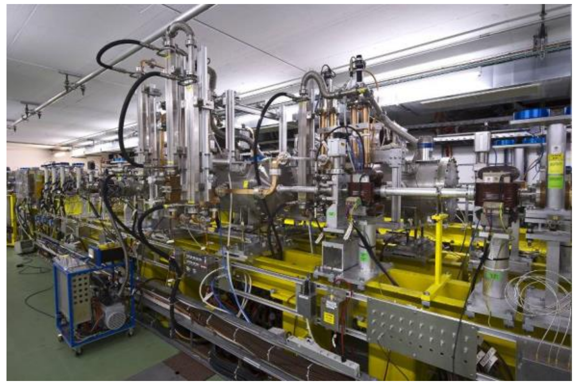
These experiments have resulted in two Oslo PhD thesis, and a number of publications.

R. Lillestøl, S. Doebert, E. Adli and M. Olvegaard, *Phys. Rev. ST Accel. Beams* **17**, 031003 (2014)

M. Olvegaard et al. *Phys. Rev. ST Accel. Beams* **16**, 082802 (2013)

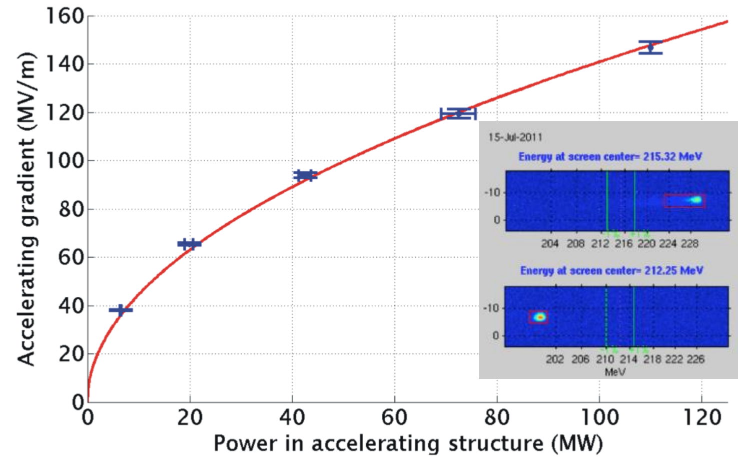
M. Olvegaard et al., *NIM A***683** 19-39 (2012)

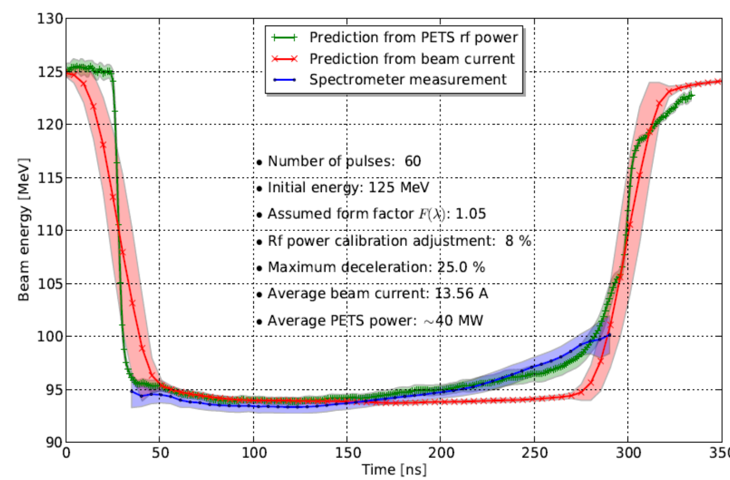
E. Adli et al. , *Phys. Rev. ST Accel. Beams* **14,** 081001 (2011)



Two-beam test stand

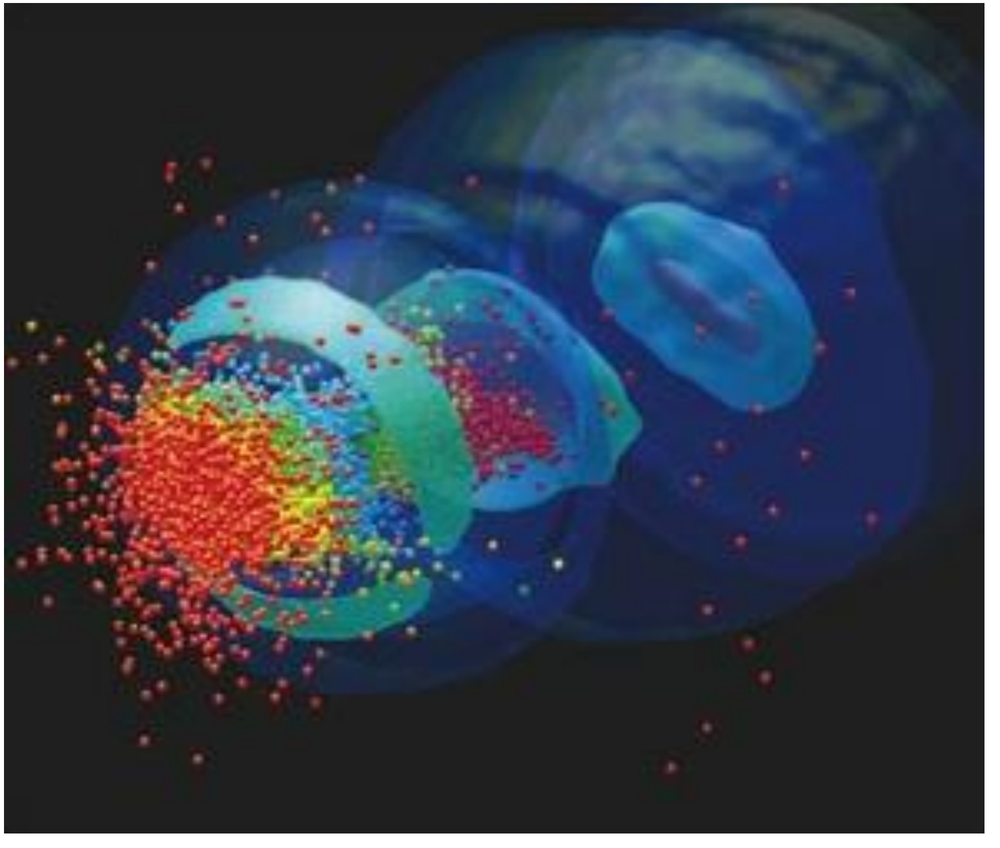
Deceleration test beam line



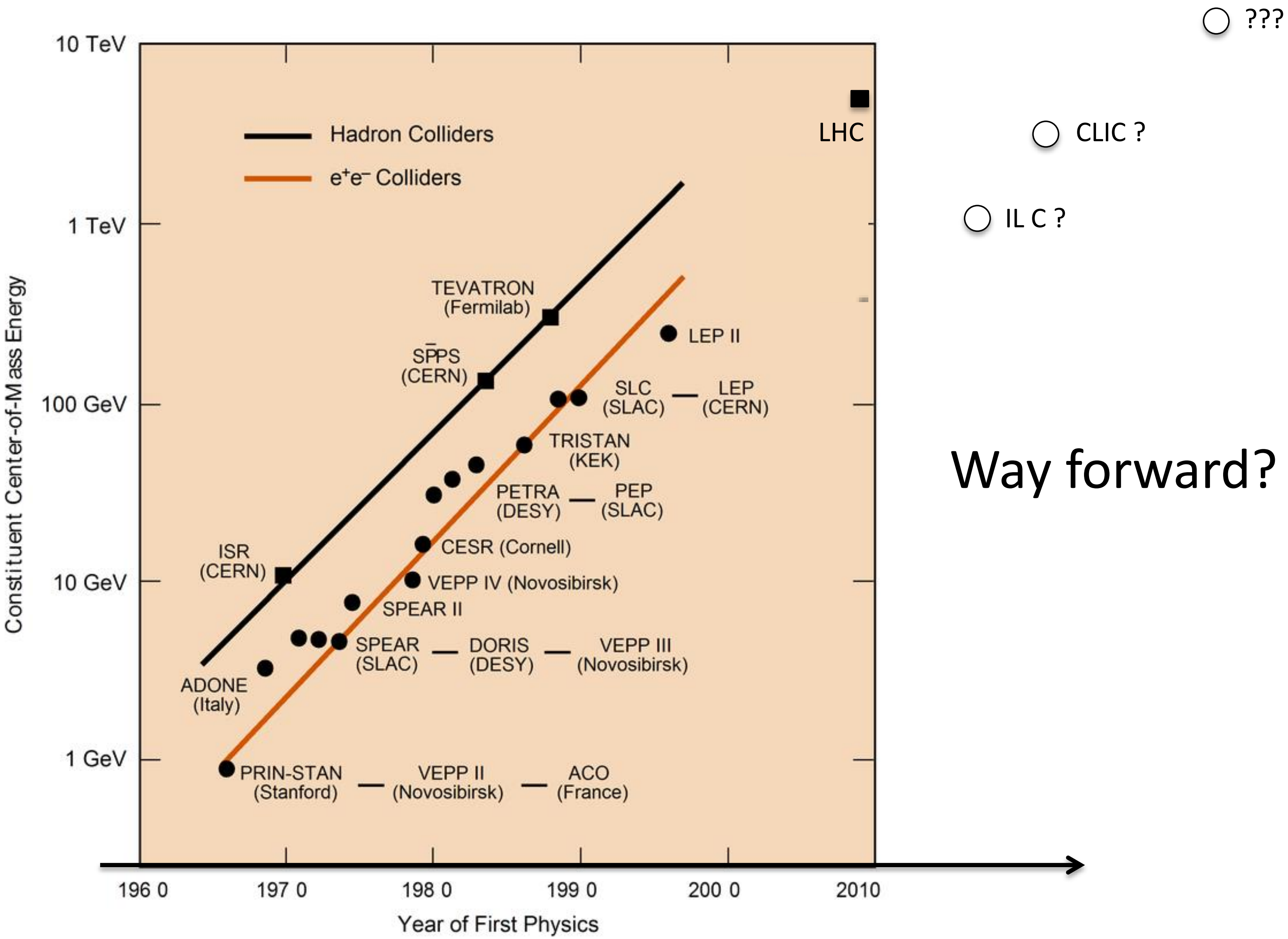


The CLIC two-Beam Acceleration scheme has now been successfully demonstrated. This has resulted the CLIC Conceptual Design report. LHC physics results will decide which machine will follow LHC.

2.2 Wakefield acceleration

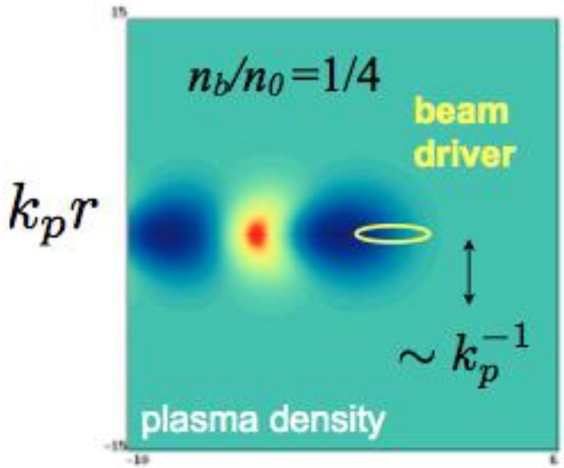


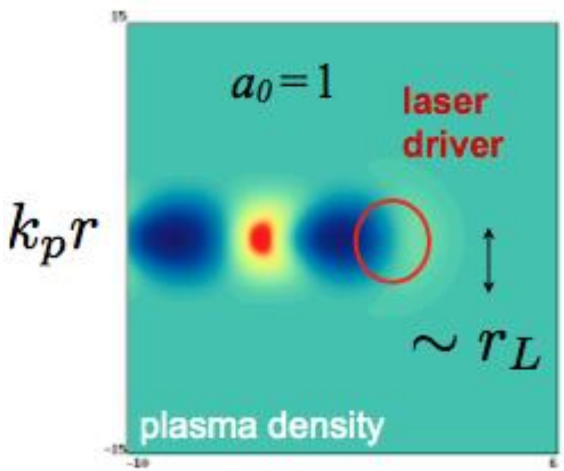
Particle collider Livingstone plot



Way forward?

Plasma wakefield acceleration

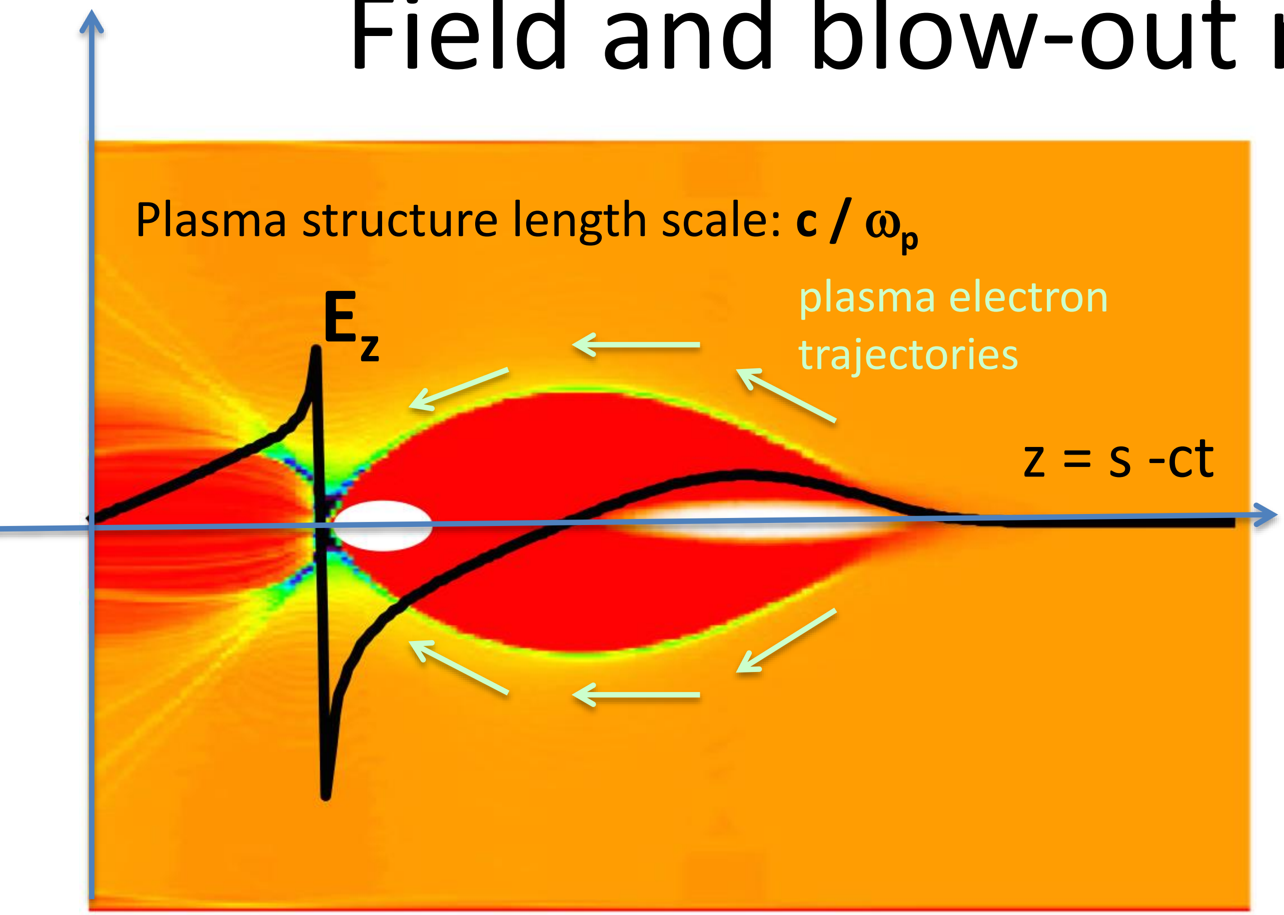




$$k_p\zeta = k_p(z - ct)$$

- **Drive a wave** in plasma by the space charge field of an
  - intense charged particle beam (beam-driven)
  - radiation pressure of an intense laser beam (laser-driven).
- **Transfer energy** from driver to witness.
  - Typical plasma densities: **$10^{14\text{-}18}$/cm^3**
  - Field strength: **10 – 100 GV/m**
  - Length scales: **λ_p~10-1000 um**
  - No surface material break down
- Ideas 1979 **T.Tajima and J.M.Dawson** (UCLA), Laser Electron Accelerator, Phys. Rev. Lett. 43, 267–270 (1979)

Field and blow-out regime



- If the driver beam current is strong enough, the **space-charge force** of driver blow away **all the plasma electrons**
- Blow-out field scale, "wave breaking" field :

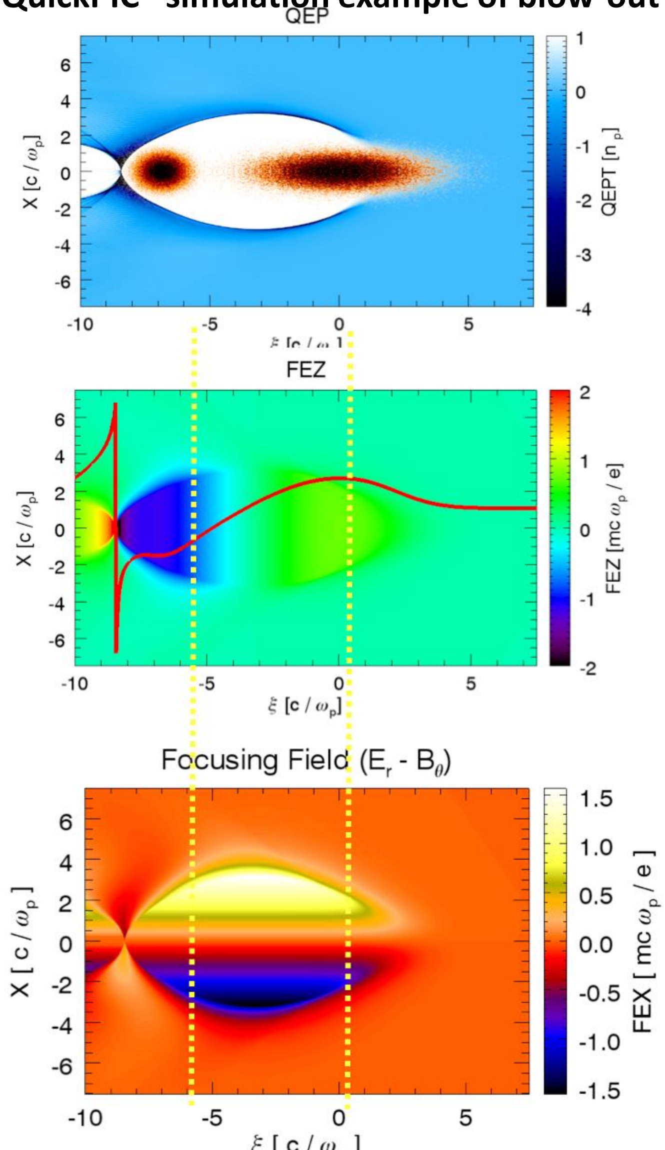
$$E_{WB} = \frac{ecn_0}{\varepsilon_0 \omega_p}$$

- Uniform layer of ions left behind.

- The plasma electrons will form a **narrow sheath** around the evacuated area, and be **pulled back by the ion-channel** after the drive beam has passed.
- The back of the blown-out region is **ideal for plasma acceleration.**

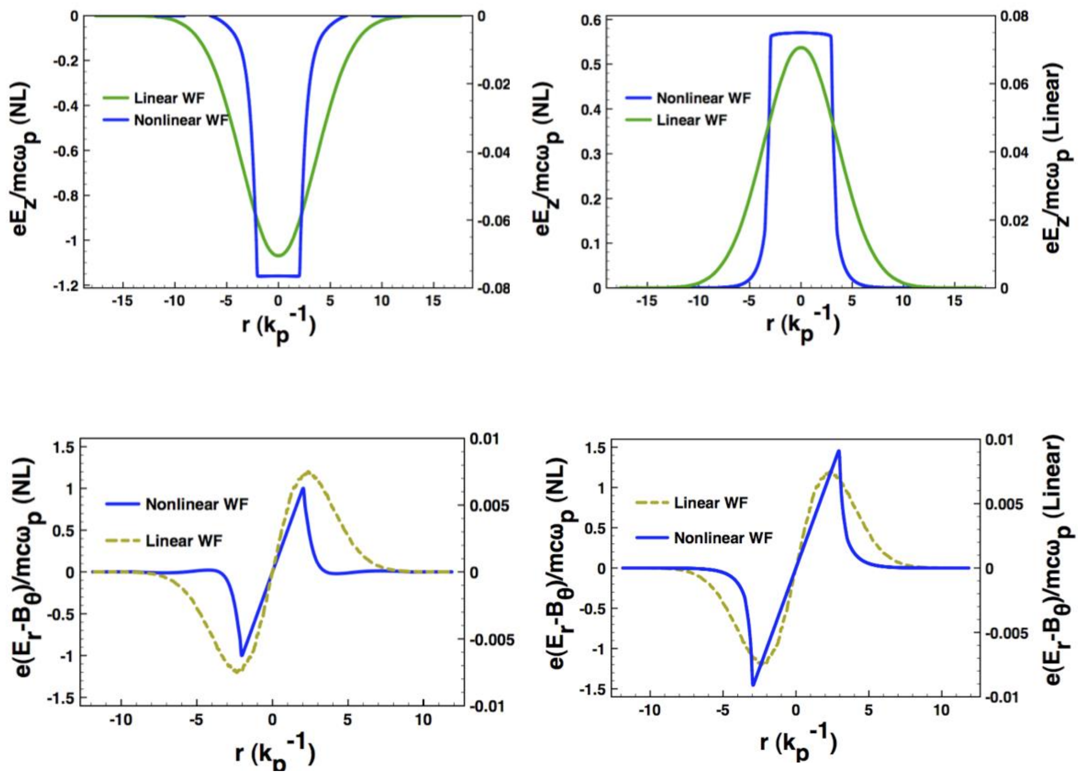
Blow-out regime: ideal for accelerating e-

"QuickPIC" simulation example of blow-out regime :



Trailing beam

Drive beam



$$\frac{\partial}{\partial r} F_z = 0$$

$$\frac{\partial}{\partial r} F_r = const.$$

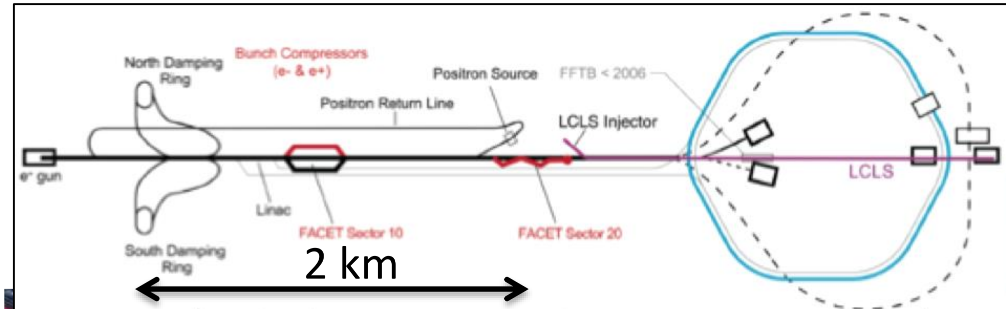
$$\frac{\partial}{\partial z} F_z = 0 \quad \text{(loaded)}$$

$$\frac{\partial}{\partial z} F_r = 0$$

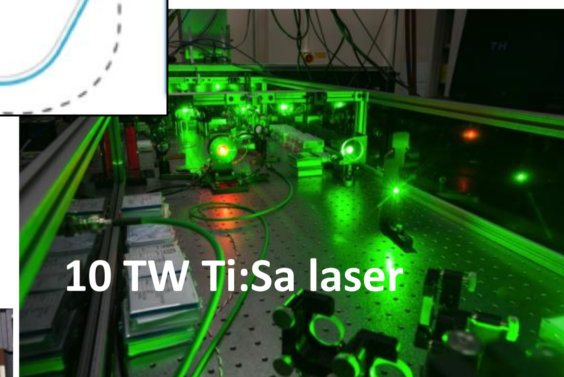
From W. Mori (UCLA)

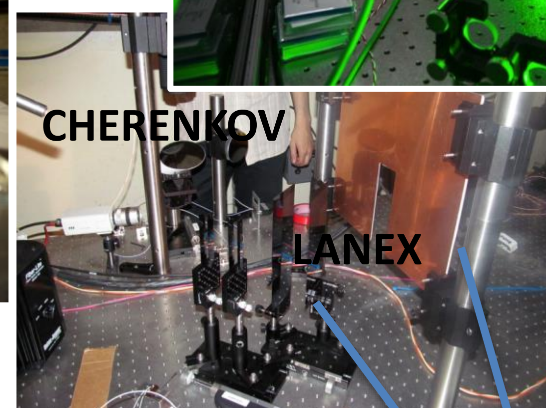
Ingredients of a plasma experiment

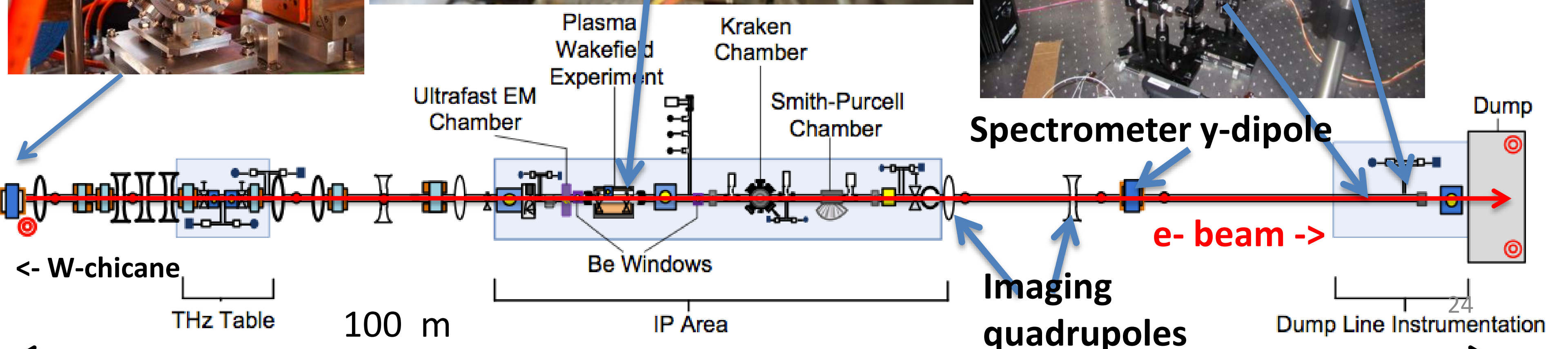
The FACET PWFA experiments at the Stanford Linear Accelerator Center



Talk for another day





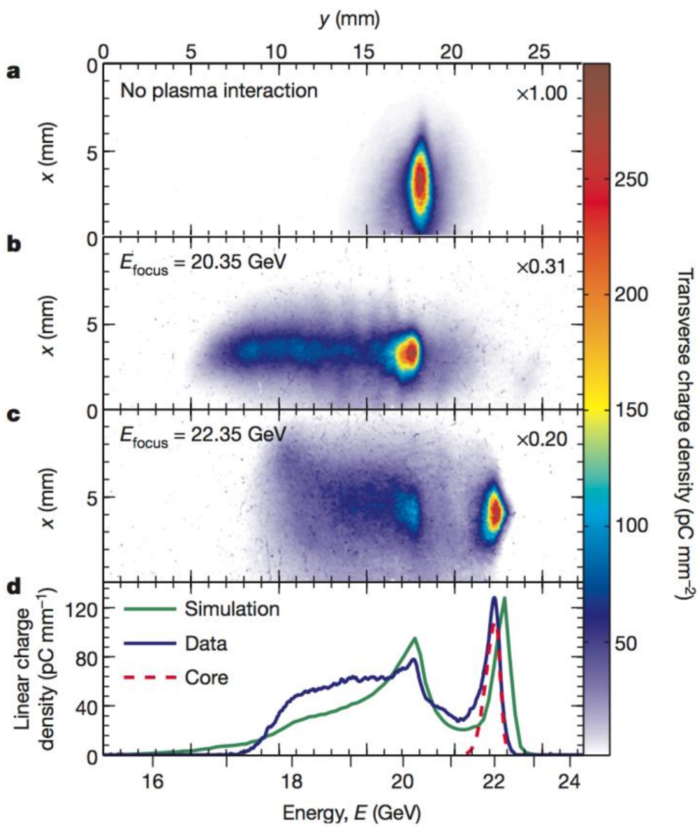


June 2013: first experimental demonstration of two-bunch acceleration in a plasma

- SLAC experiments started in 2011 and led to ground breaking results.
- This has opened opportunities for Oslo students to participate in world class plasma experiments at CERN and at Stanford University/SLAC.

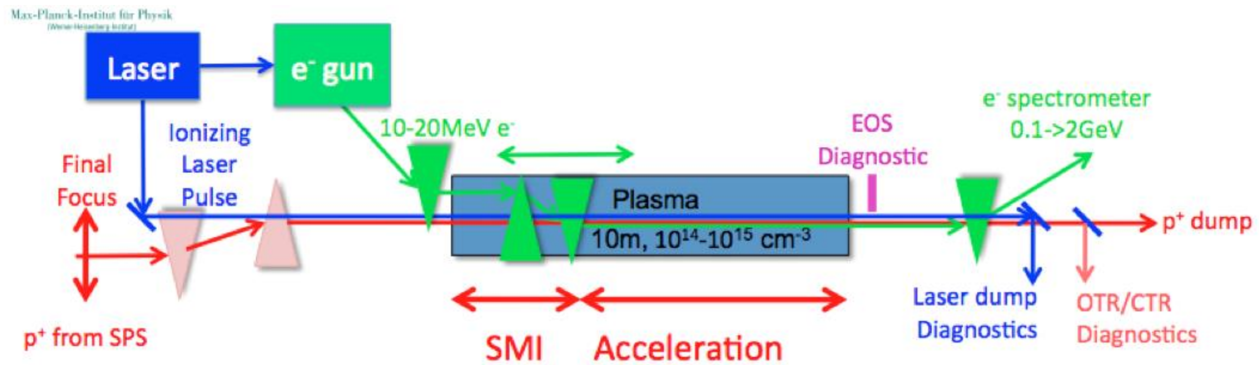
Acceleration of a witness beam, with high efficiency (>30% wake to beam), high gradient (5 GV/m) and low energy spread (~1%) recently demonstrated at SLAC/FACET, at a plasma of density 5e16/cm^3. This is the first **experimental demonstration** of plasma acceleration of a beam, paving way for a potential revolution in how particle acceleration is done.

- M. Litos et al., Nature, 6 November 2014 (10.1038/nature13882)
- E. Adli et al. *NIM A* (2015), dx.doi.org/10.1016/j.nima.2015.02.003
- S. Li et al., *Plasma Phys. Control. Fusion* 56, 084011 (2014)
- N. Vafaei et al., *Phys. Rev. Lett.* 112, 025001 (2014)
- W. An et al., *Phys. Rev. ST Accel. Beams* 16, 101301 (2013)
- …

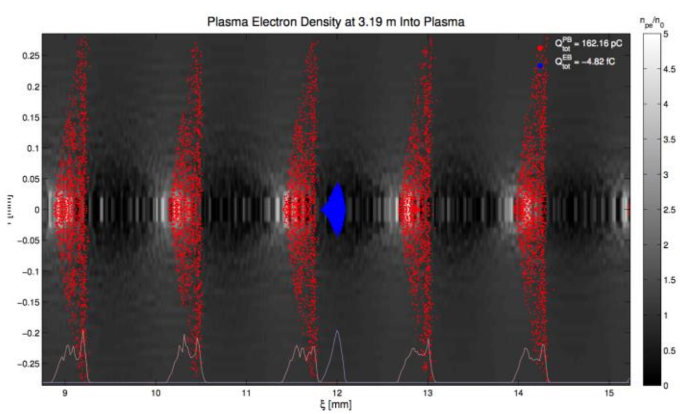


The AWAKE experiment at CERN

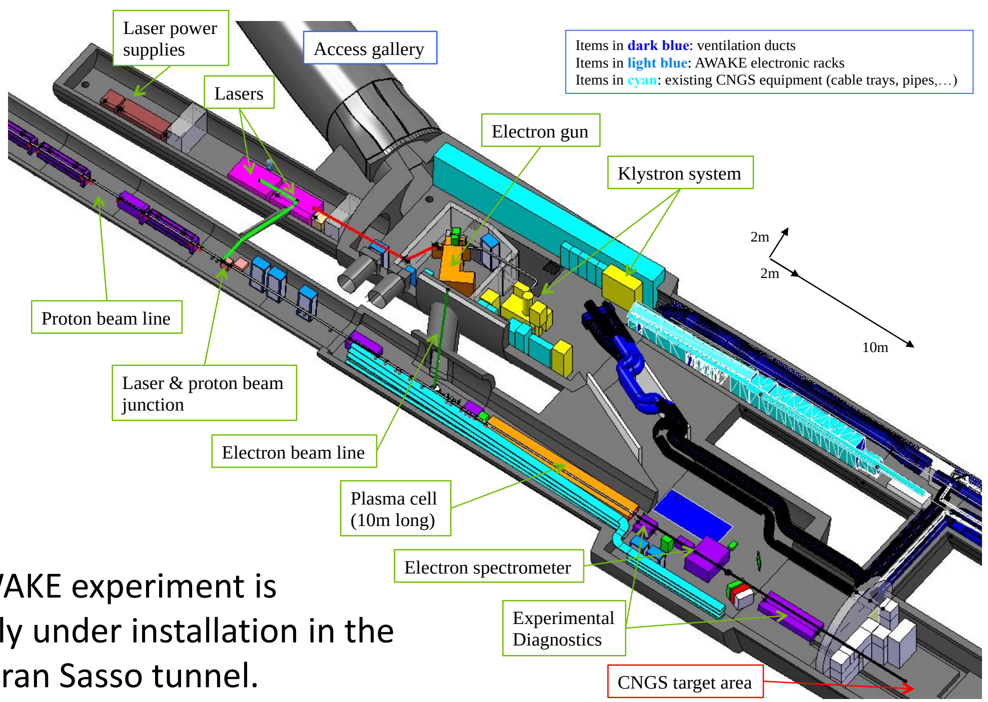
Surfing the wave, our group has extended its PWFA activities to the new PWFA experiment approved at CERN.



AWAKE: "A Proton Driven Plasma Wakefield Acceleration Experiment at CERN". Idea: use CERN proton bunches with kJ energies as a PWFA driver. The proton bunch drives self-modulated wake fields with accelerating fields of about 1 GV/m over 10 meters. An e- bunch will sample the wake. **First beam: 2016.**



The low-density long beam will self-modulated and generate intense wake fields. **PIC simulations performed by Veronica Olsen (FI, Oslo)**



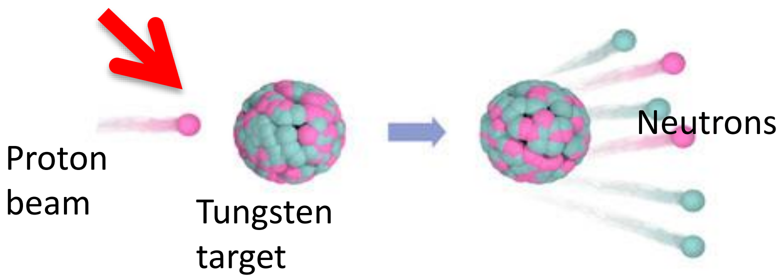
The AWAKE experiment is currently under installation in the CERN Gran Sasso tunnel.

2.3 European Spallation Source (ESS)

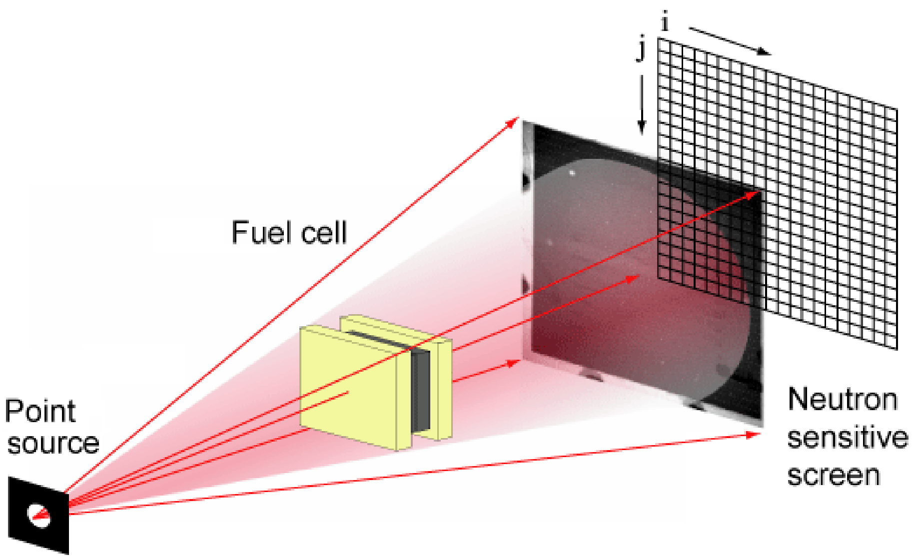
European Spallation Source (ESS)

Spallation:

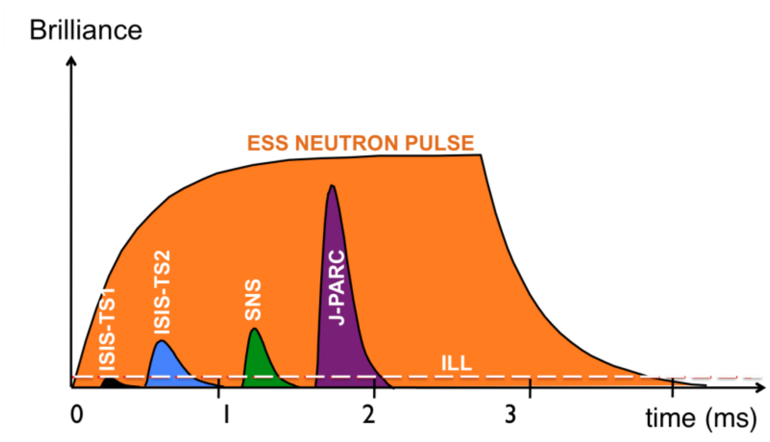
5 MW, 2 GeV



Material science with Neutrons:



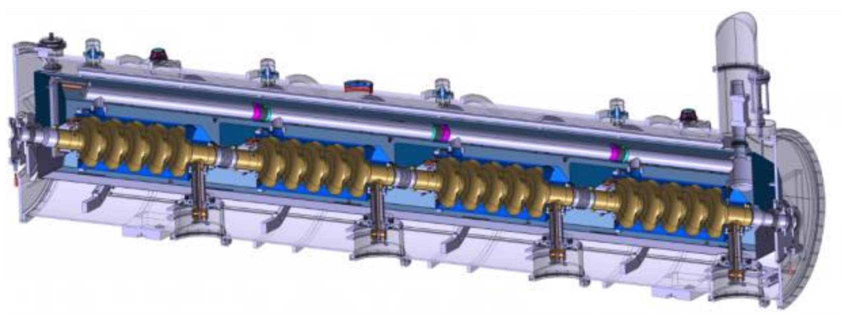
ESS potential:



- ESS: largest accelerator project in Scandinavia up to now, and in foreseeable future.
- Norway is committed to contribute In-Kind ≈150MNOK.

Beam power and machine protection

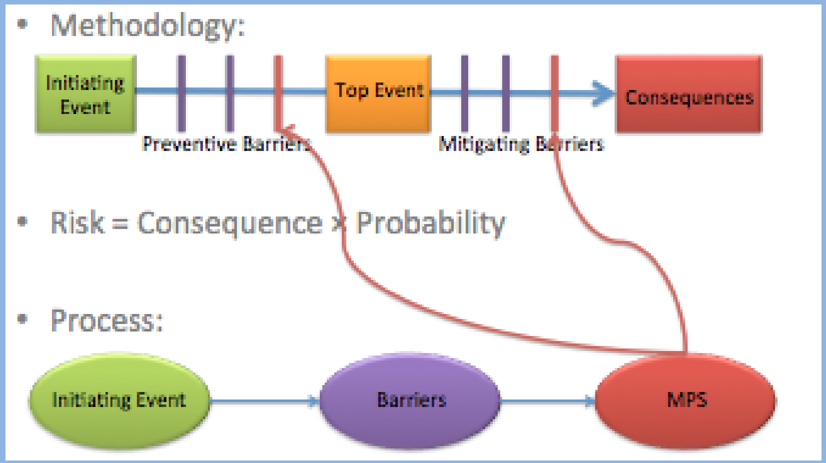
- The accelerator will be the world's most powerful **proton driver**.
- Superconducting part: 310 m of Niobium Cavities in 2.1 K (liquid) He bath.



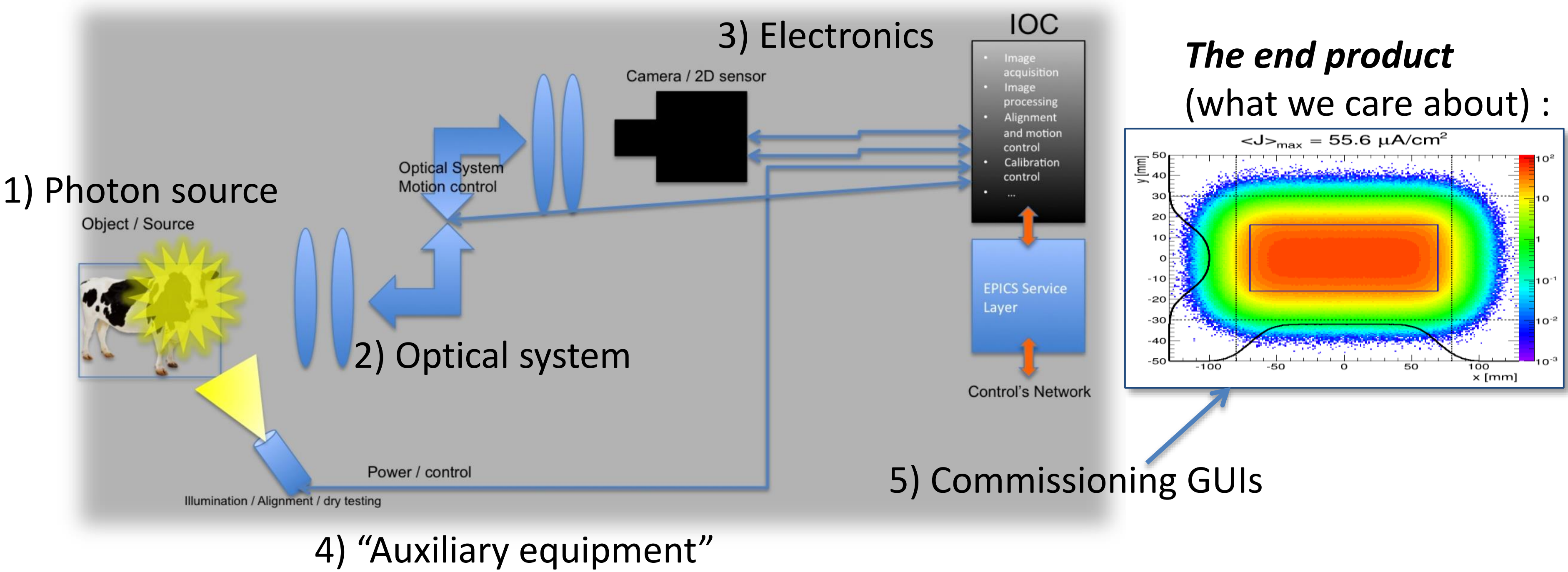
- **Proton-driver**: same technology as needed in an Accelerator Driven Nuclear Power Plant

- Beam loss could damage superconducting structures.
- Machine protection is essential.

Oslo: currently involved in the development of a novel and robust Machine Protection System:



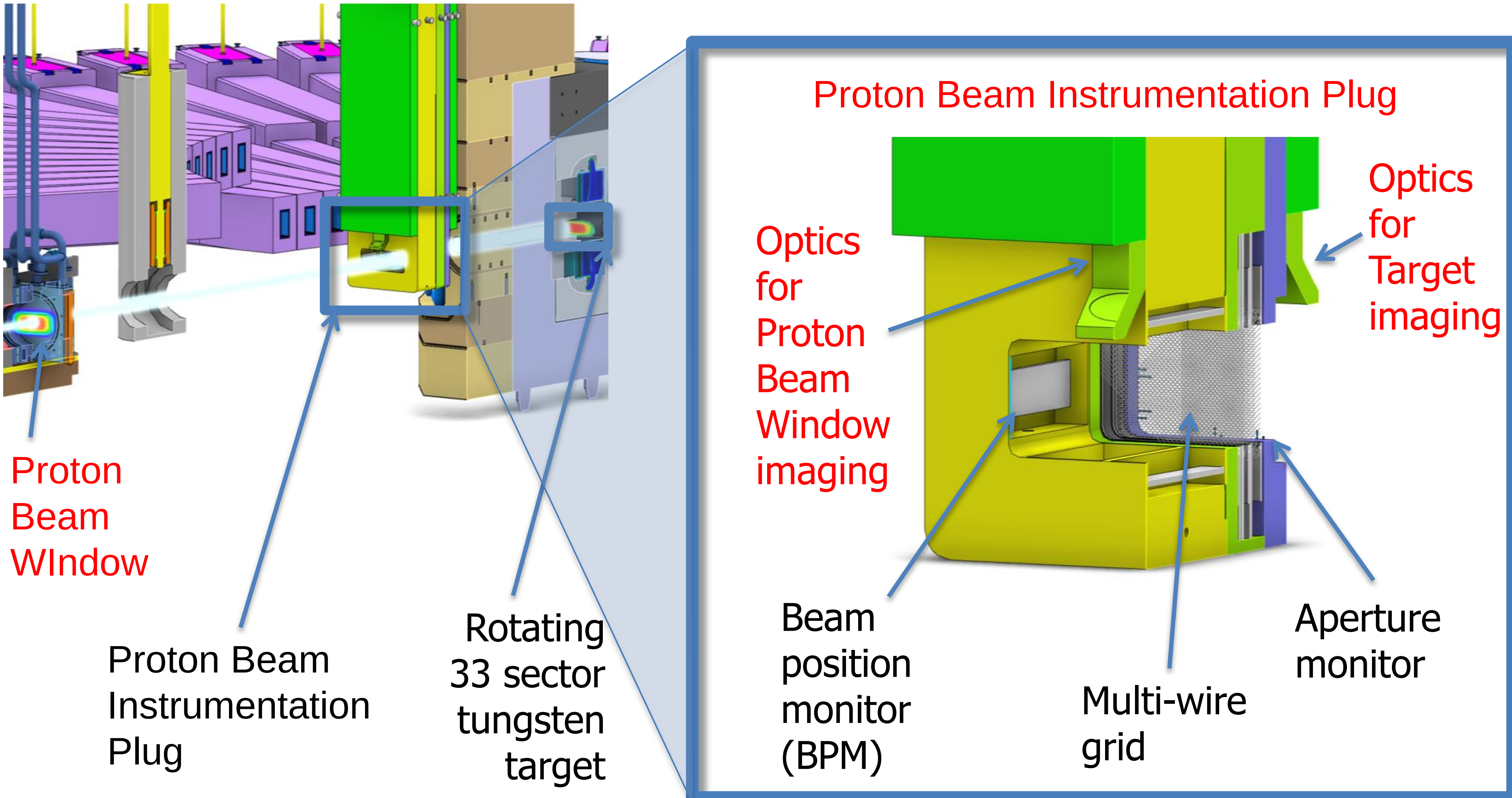
Proton Beam Imaging Systems



Problem: challenging environment in the target region

- High neutron flux set constraints on component choices
- Not accessible once put in place. Specs: replaced only after 5 years.

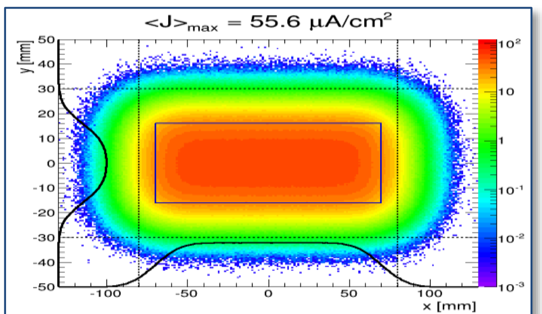
Proton Beam Imaging Systems



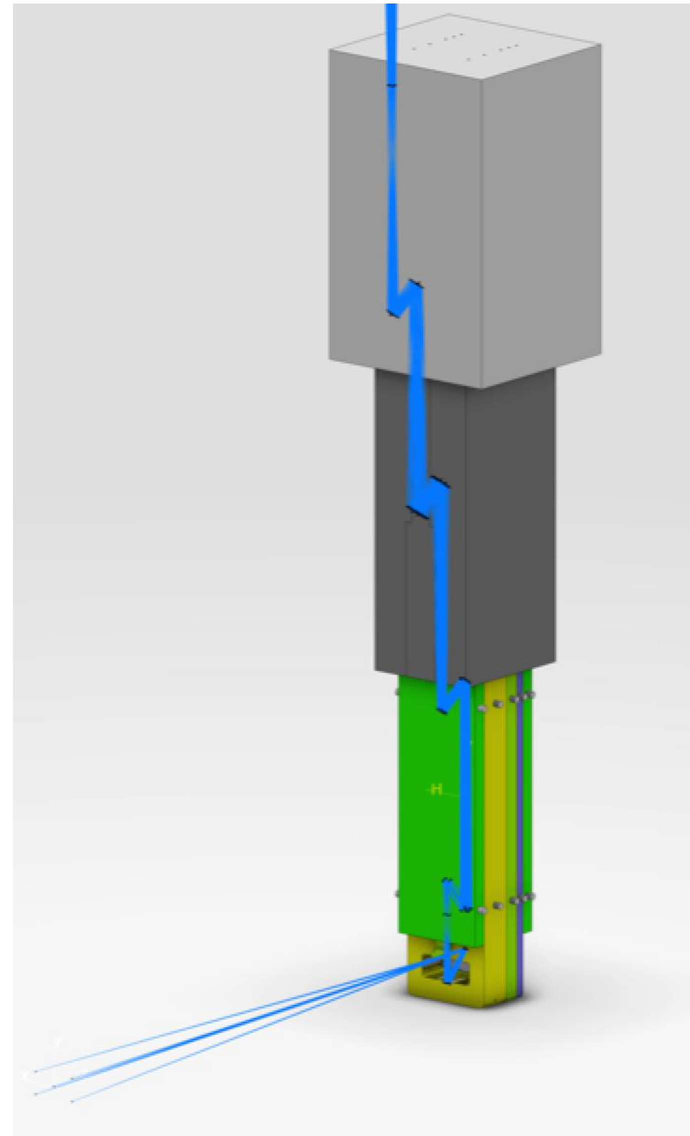
Upstream: position, current, aperture, and loss monitors

Main challenges

1) Photon source: metallic coating, required R&D

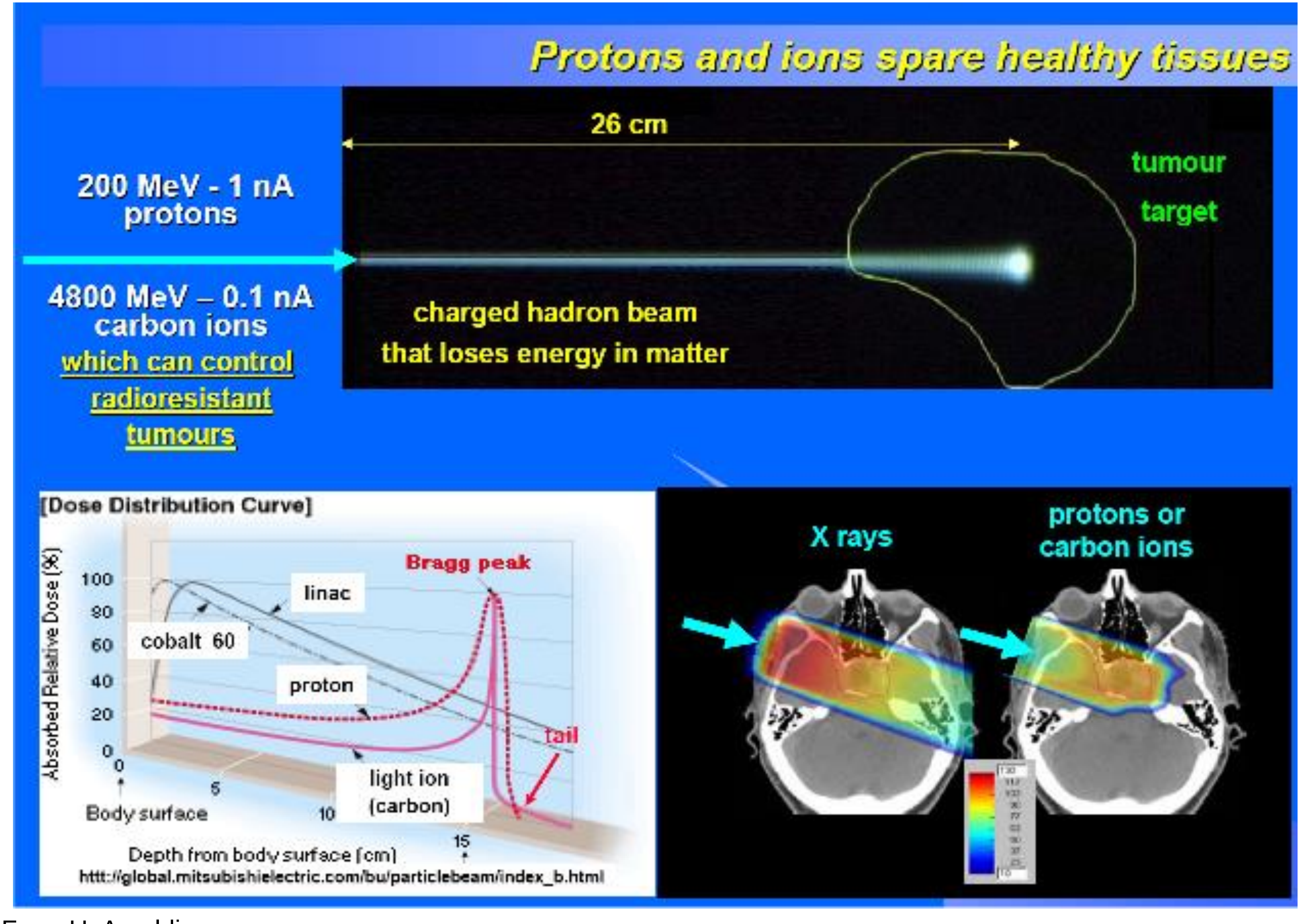


2) Optical system for light transport: shielding constraints



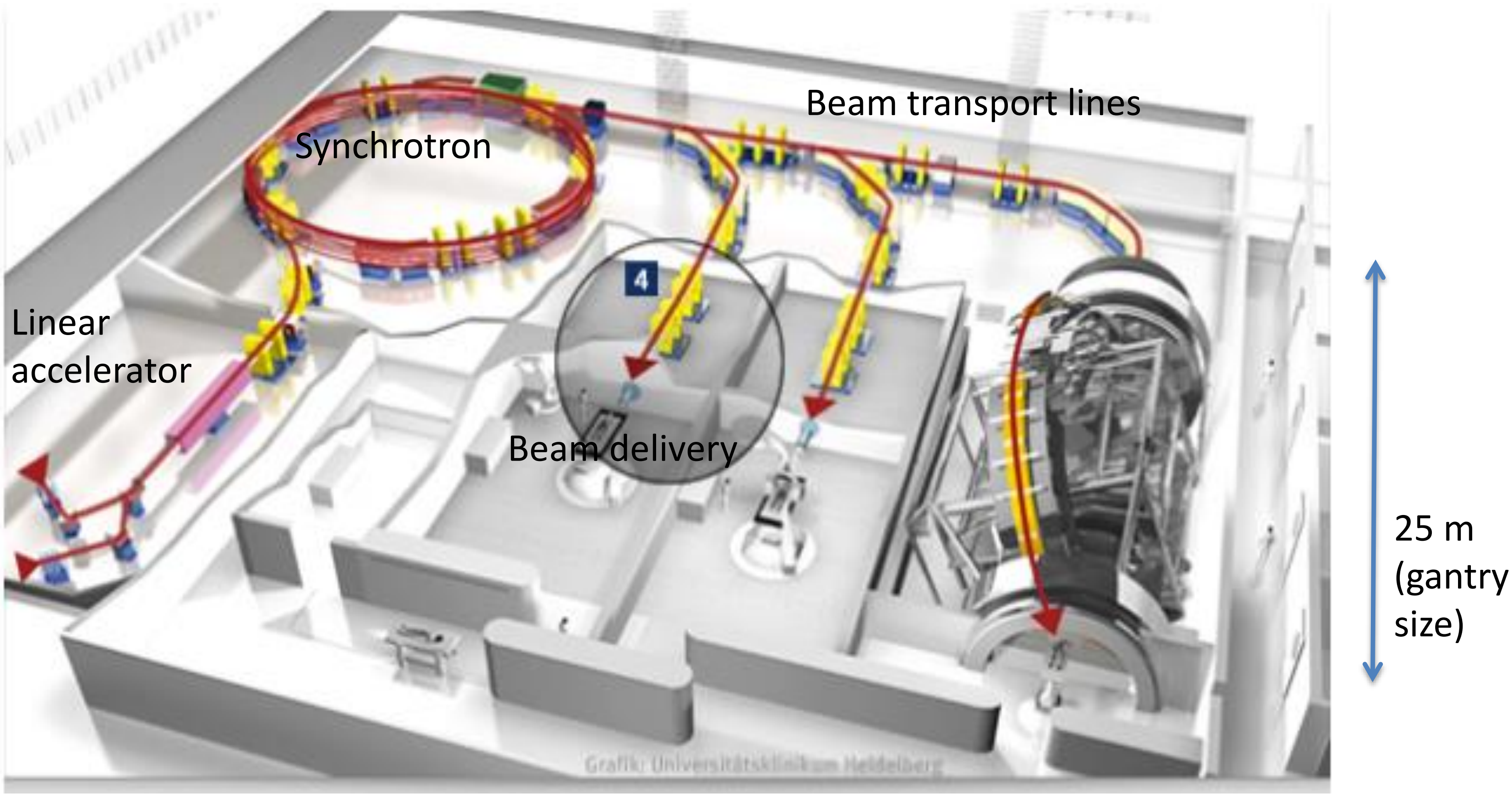
2.4 Hadron therapy

Advantages of hadron therapy



From U. Amaldi

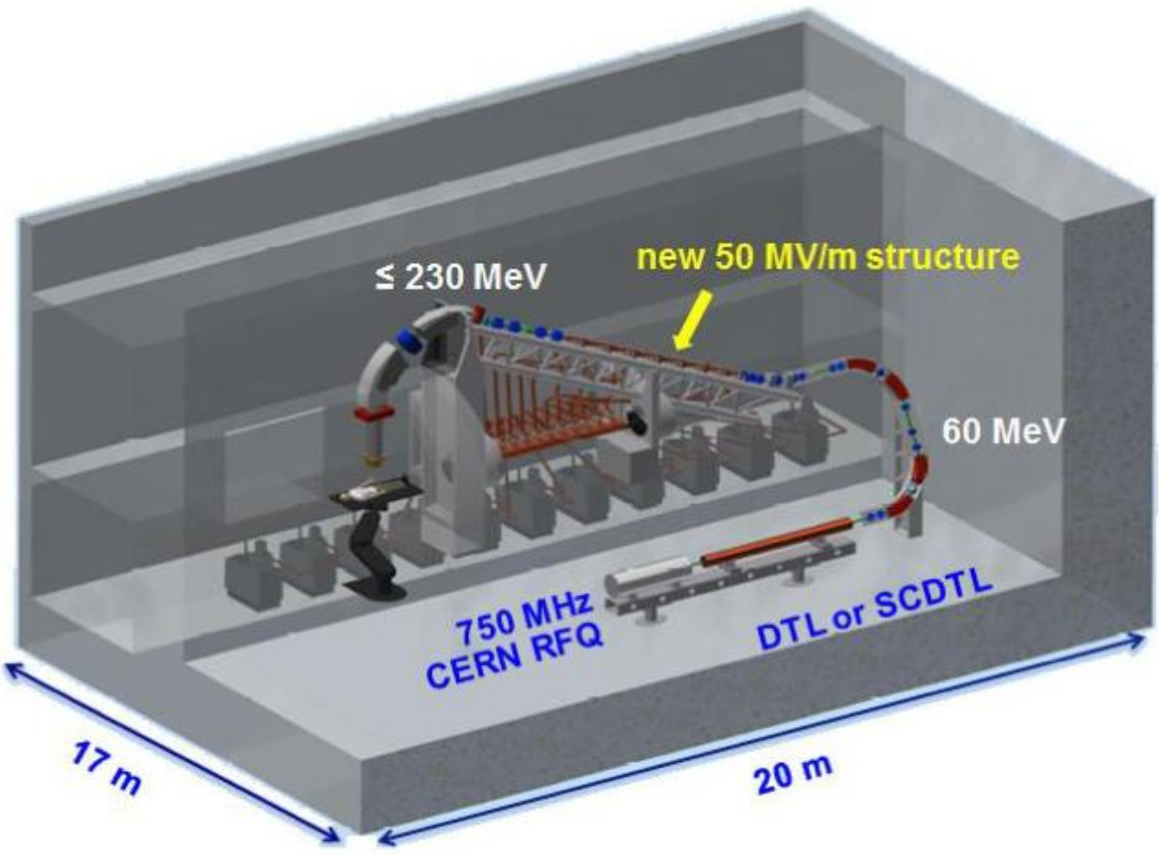
Hadron therapy accelerators



[Heidelberg Ion-Beam Therapy Center (HIT)]

H.H. Bjerke, MSc Thesis, “Application of Novel Accelerator Research for Particle Therapy”, 2014

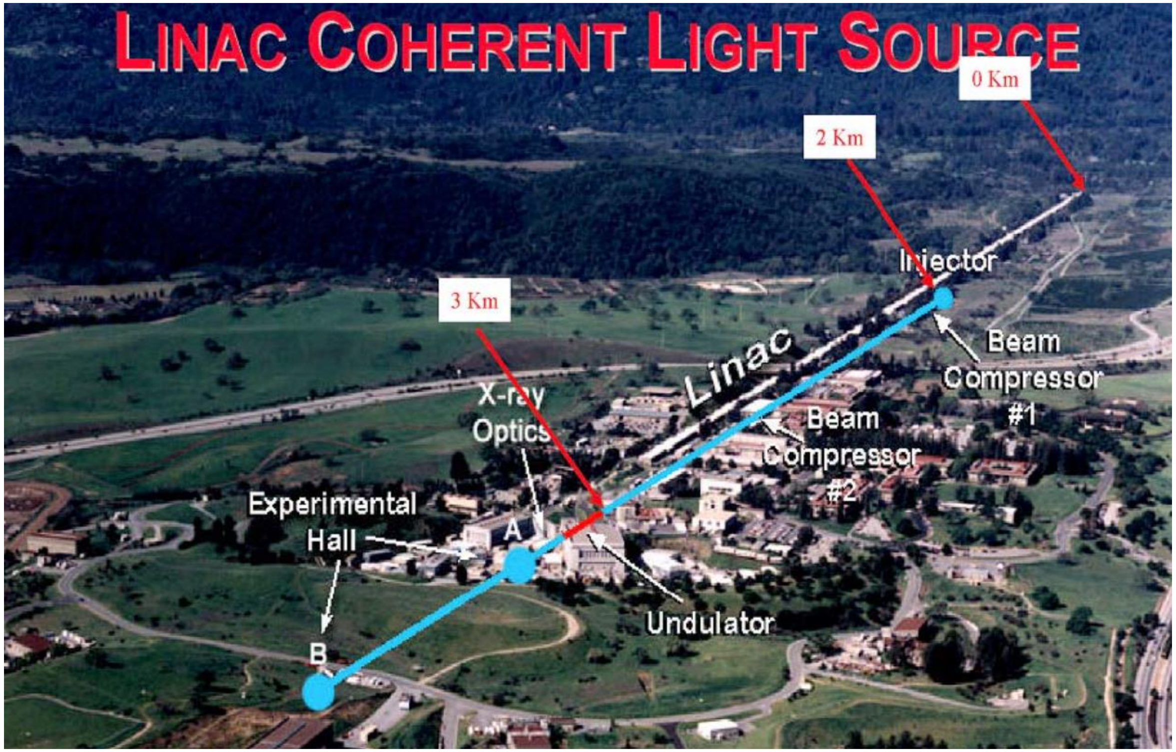
New concepts based on CLIC technology



From U. Amaldi

- Decrease size and therefore cost of hadron therapy systems.
- CLIC-like structures have so high gradients that everything can be mounted in gantry.
- Additional advantage of fast energy changes (fast screening).

2.5 Free-Electron Lasers (FEL)

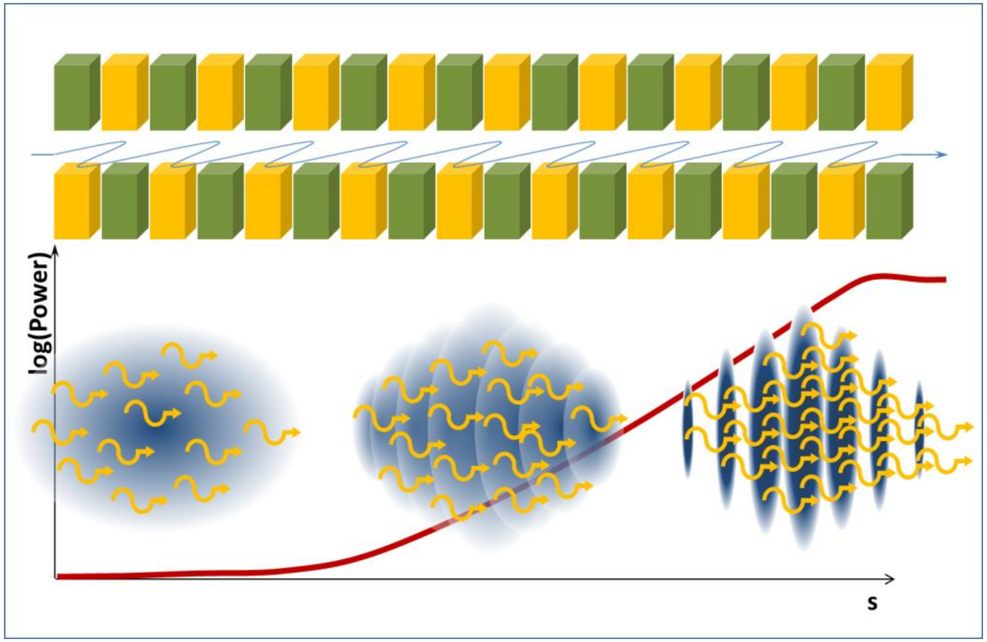


Sources of X-ray radiation

- Accelerated electrons radiate electromagnetic radiation (antenna).
- Due to the high electron energy in synchrotrons, this radiation (synchrotron radiation) extents into the X-ray regime.
- The extremely high intensity of these X-rays is used for experiments.
- World-wide there are about 50 dedicated synchrotrons for X-ray production (light sources).

Soleil in Paris: Anlage und schematischer Aufbau

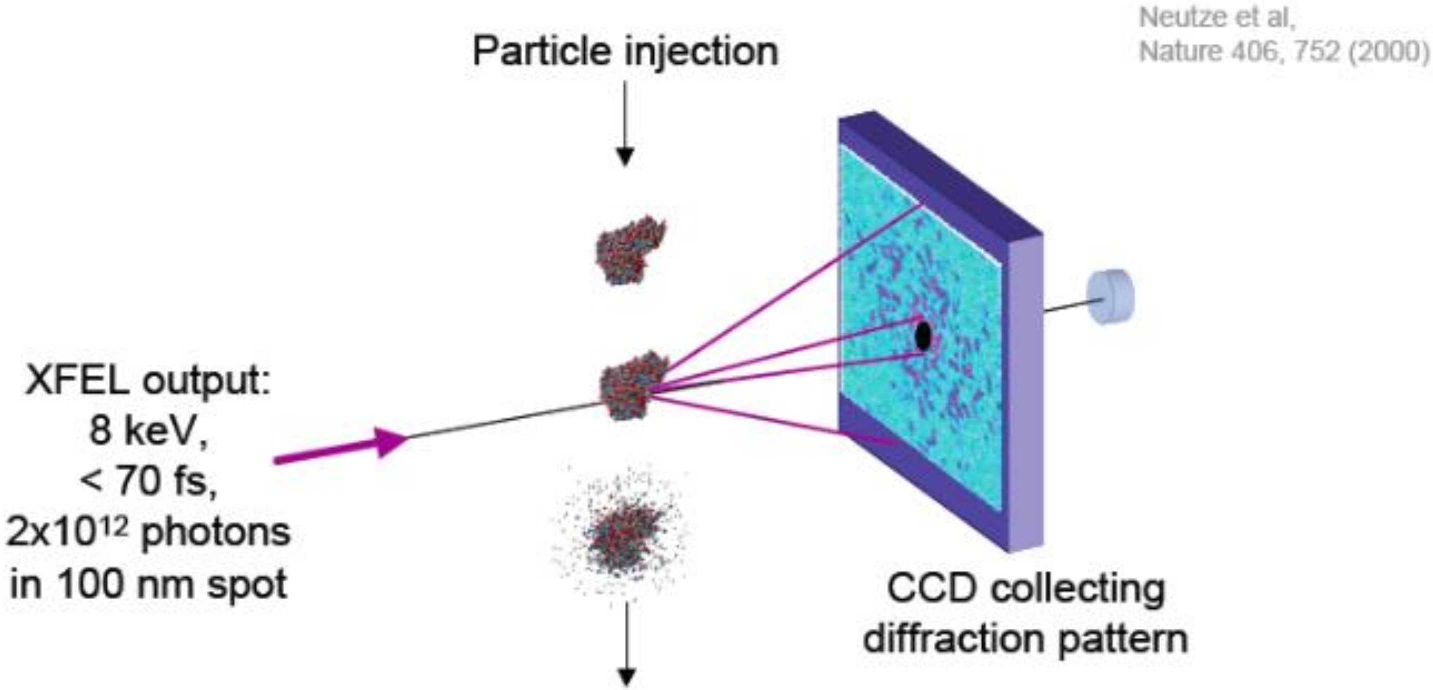
Free-electron laser (FEL)



Undulatorprinzip und Mikrobunch-Entwicklung

- Based on a linear accelerator followed by an undulator.
- Particles move on sinus trajectory.
- Via interaction of particles and produced X-rays, micro-bunches form.
- Due to that the particles radiate coherently (laser properties).
- 10^{10} higher X-ray intensity compared to synchrotrons.
- Only 2 FELs in hard X-ray regime running at the moment. High current interest.

Experiments with X-rays



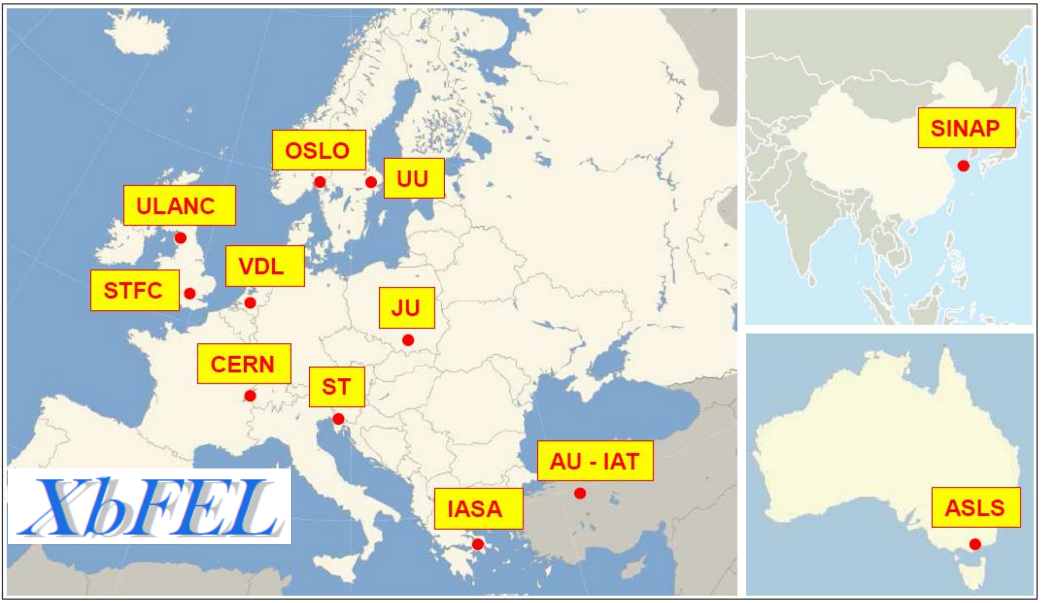
- Due to short wavelength of X-rays, very small structures are resolvable.
- Pictures of smallest biological objects: cells, proteins.

- Synchrotron X-ray source: Averaging over long time period necessary.
- FELs: Nearly 1-pulse imaging is possible. This allows to study the dynamics of molecules.

The X-band FEL collaboration

- Idea: Use new CLIC-like acceleration to build FELs.
- New structures have higher gradient and FELs can (hopefully) be build shorter and cheaper. Hopefully, also smaller countries could effort such FELs.
- International collaboration of interested institutes (design report within 3 years).

Example of X-band test facility at CERN



ST	*Elettra - Sincrotrone Trieste, Italy.*
CERN	*CERN Geneva, Switzerland.*
JU	*Jagiellonian University, Krakow, Poland.*
STFC	*Daresbury Laboratory Cockcroft Institute, Daresbury, UK.*
SINAP	*Shangai Institute of Applied Physics, Shanghai, China.*
VDL	*VDL ETG T&D B.V., Eindhoven, Netherlands.*
OSLO	*University of Oslo, Norway.*
IASA	*National Technical University of Athens, Greece.*
UU	*Uppsala University, Uppsala, Sweden.*
ASLS	*Australian Synchrotron, Clayton, Australia.*
UA-IAT	*Institute of Accelerator Technologies, Ankara, Turkey.*
ULANC	*Lancaster University, Lancaster, UK.*

3. Summary

- Particle accelerators, **a coherent field** of physics with many international collaborations.

- Particle accelerator studies and particle accelerator research include components from our three pillars: **Theory, Computation and Experiment**.

- Our activities in Oslo, as a Norwegian hub for accelerator expertise, spans a large spectrum of accelerator activities
  - Fundamental R&D
  - HEP machine design
  - Other applications.

- If you are interested in participating (summer, master of PhD student) please contact Erik Adli erik.adli@fys.uio.no

Nordic Particle Accelerator School
August 14-22, 2017, Lund, Sweden

Nordic Particle Accelerator School 2017

Lund University, Sweden

August 14-22, 2017

All costs – travel, lodging and food – will be covered by the school.

For questions and in order to register, **please contact Assoc. Professor Erik Adli by March 8**:
Contact: erik.adli@fys.uio.no
More information: https://npap.eu/summer-school-npas2017/

Topics:
An introductory course on the physics of particle accelerators, aimed at Bachelor and Master students in Physics and Electrical Engineering. Students will receive an introduction to accelerator based science and learn how modern particle accelerators work.

Lund, Sweden

Preparation team:
Lund University: Anders Karlsson
MAX IV Laboratory: Francesca Curbis, Sverker Werin
European Spallation Source: Christine Darve
Uppsala University: Maja Olvegard
Aarhus University: Søren Pape Møller
University of Oslo: Erik Adli
University of Jyväskylä: Pauli Heikkinen

Lund is home to Scandinavia's largest particle accelerator facilities, the European Spallation Source and the MAX IV Laboratory. The school includes visits to both facilities.

Thank you for your attention!