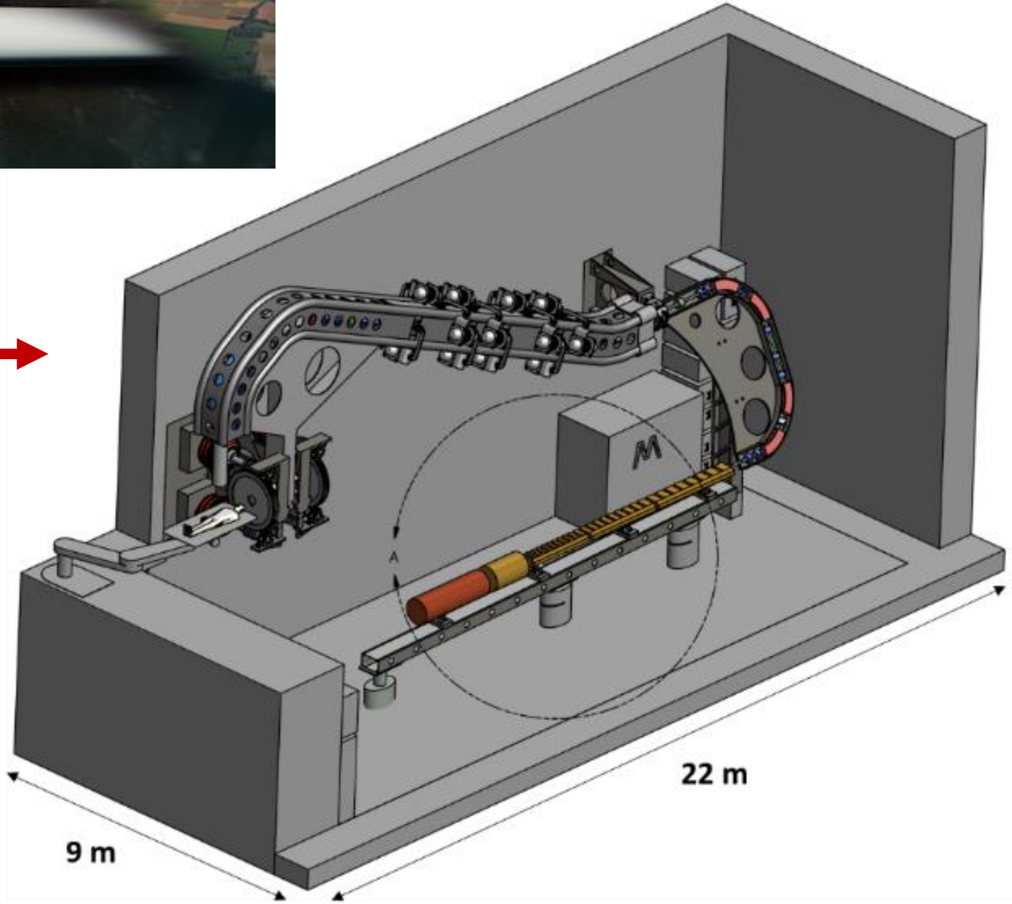
Medical applications of high-frequency, high-gradient accelerating structures

Walter Wuensch, CERN

The theme of this presentation

How technology developed for high-energy particle physics may also be important for cancer therapy.



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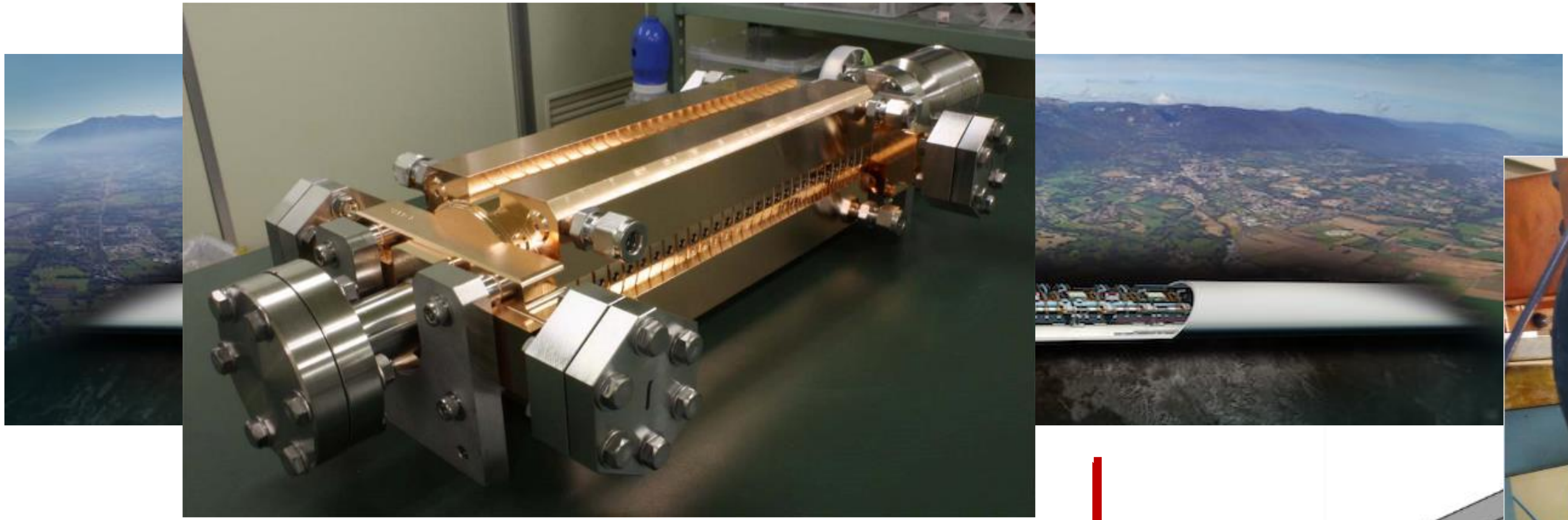

How technology developed for
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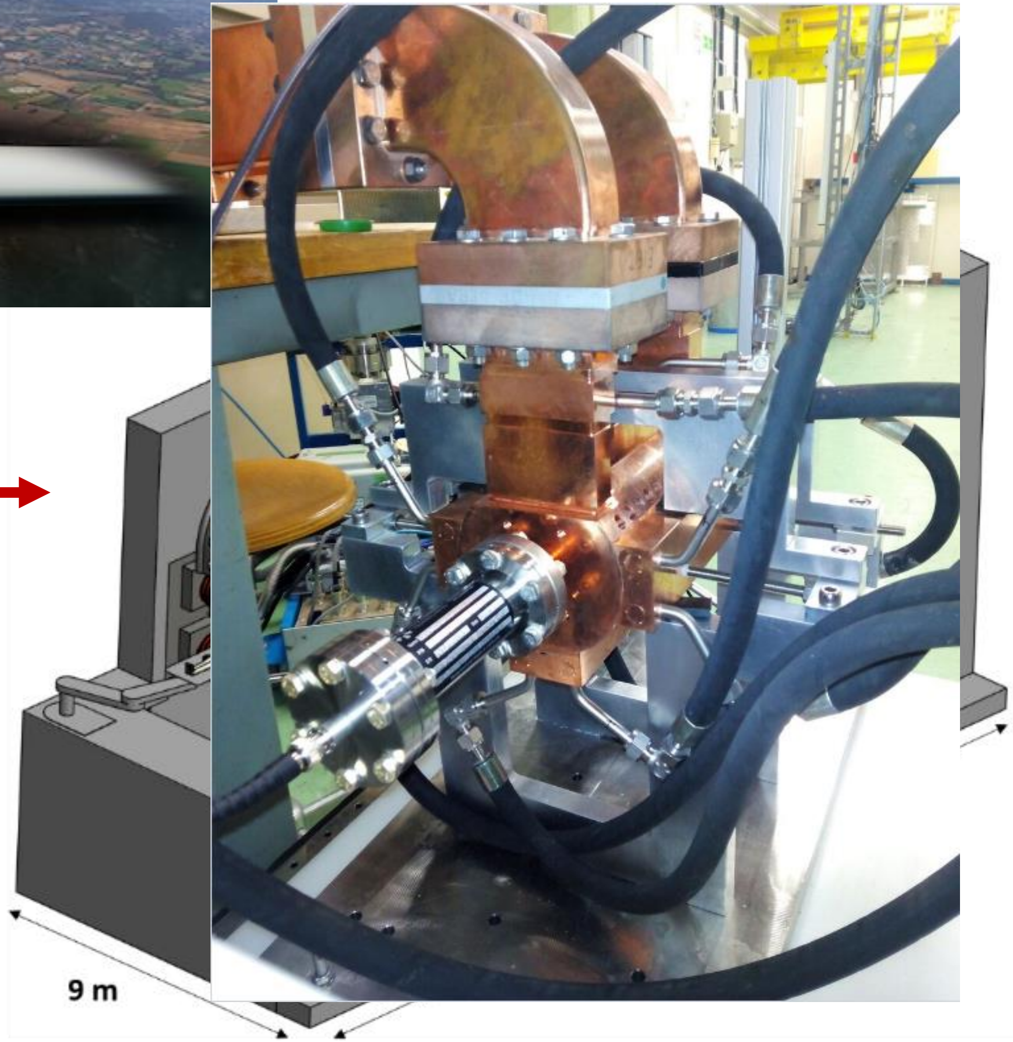
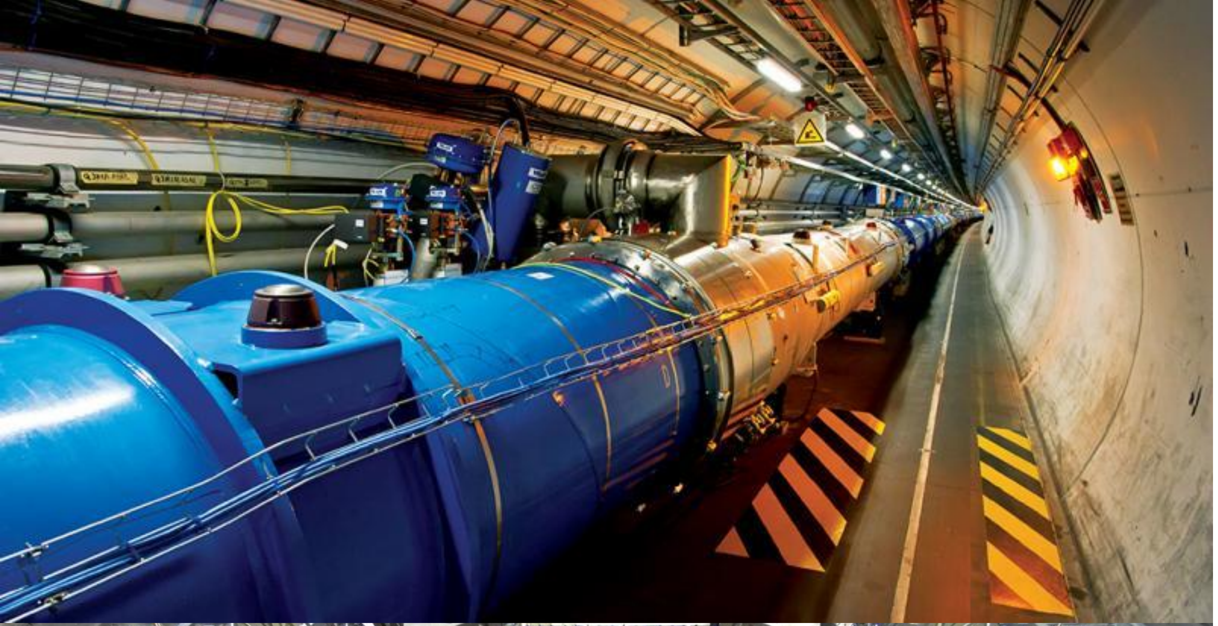
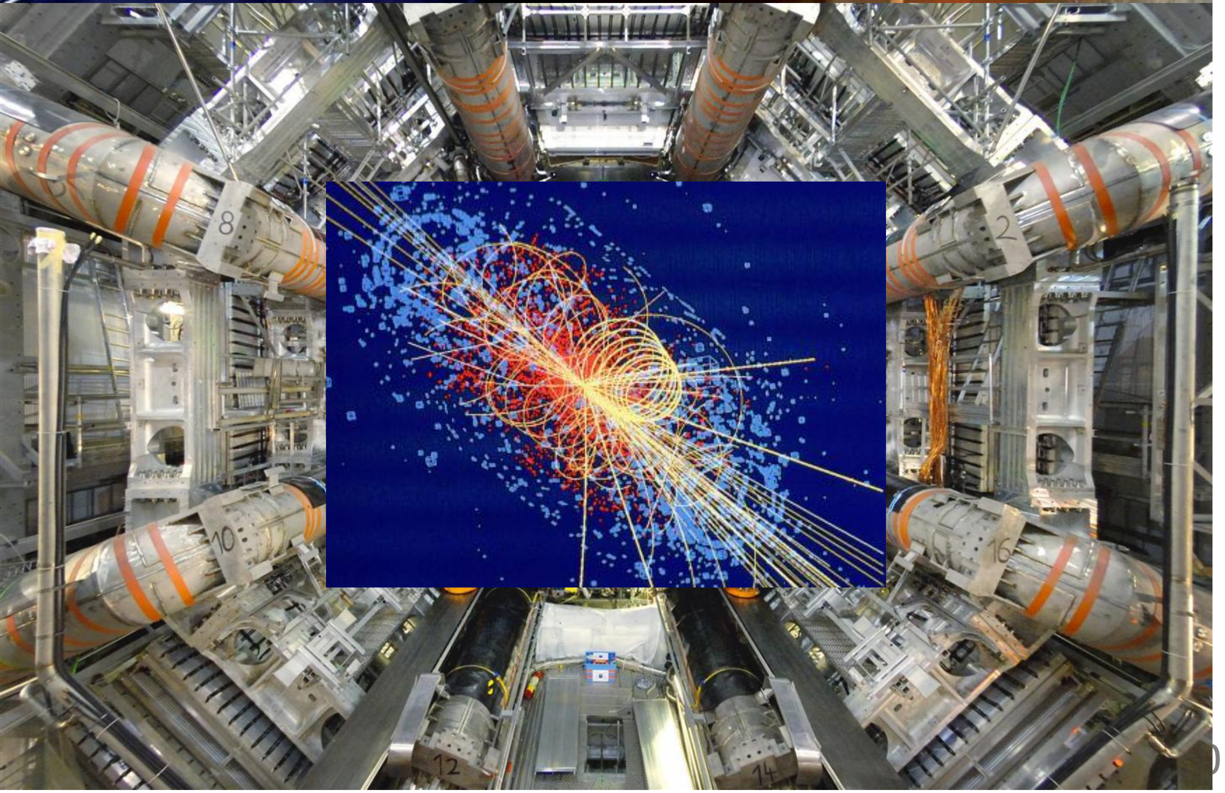


Outline

- Introduction to CLIC and physics motivation
- High-gradient accelerating technology developed by CLIC
- This technology applied to hadron accelerators

Context



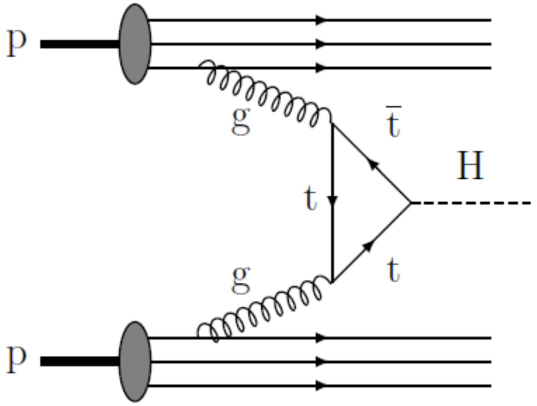


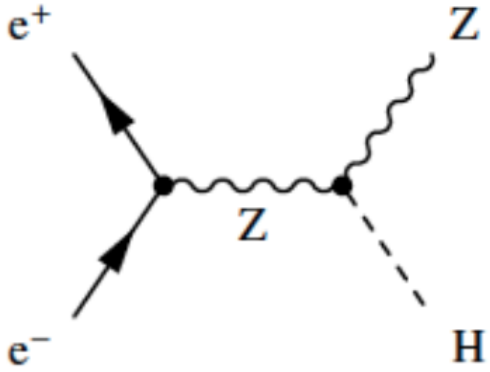
CERN is currently running the LHC at full energy with scientific program extending into mid-2020s.

Higgs discovered, standard model going strong but huge questions remain unanswered. What’s next and how?

What direction will high-energy physics take?

pp/e$^+$e$^-$ collisions





p-p collisions	e$^+$e$^-$ collisions
Proton is compound object → Initial state not known event-by-event → Limits achievable precision	**e$^+$/e$^-$ are point-like** → Initial state well defined (√s / polarisation) → High-precision measurements
High rates of QCD backgrounds → Complex triggering schemes → High levels of radiation	**Cleaner experimental environment** → Trigger-less readout → Low radiation levels
High cross-sections for **colored-states**	Superior sensitivity for **electro-weak states**
High-energy **circular** pp colliders feasible	High energy (>≈350 GeV) e$^+$e$^-$ requires **linear** collider

High-energy physics strategy

Fabiola Gianotti
CERN Director General
26/6/2017

Full exploitation of the LHC:
- ❑ successful operation of the nominal LHC until end 2023 (Run 2, LS2, Run 3)
- ❑ construction and installation of the LHC upgrades: LIU and HL-LHC

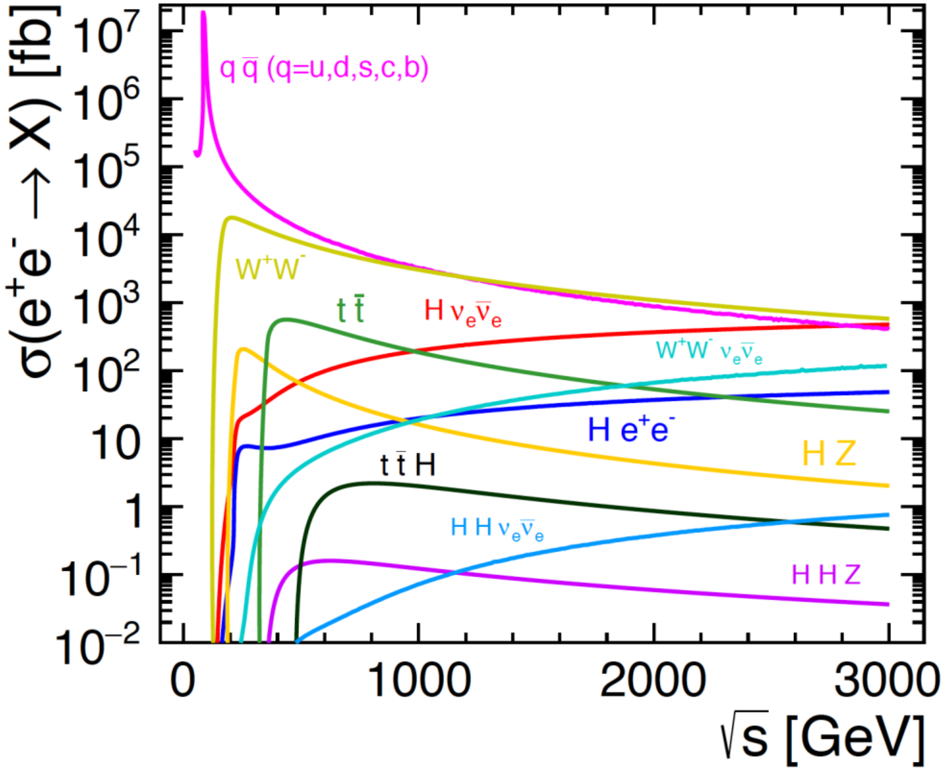
Scientific diversity programme serving a broad community:
- ❑ ongoing experiments and facilities at Booster, PS, SPS and their upgrades (HIE-ISOLDE, ELENA)
- ❑ participation in accelerator-based neutrino projects outside Europe (presently mainly LBNF in the US) through the CERN Neutrino Platform

Preparation of CERN's future:
- ❑ vibrant accelerator R&D programme exploiting CERN's strengths and uniqueness (including superconducting high-field magnets, AWAKE, etc.)
- ❑ design studies for future high-energy accelerators: CLIC, FCC (includes HE-LHC)
- ❑ studies of future opportunities of diversity programme: Physics Beyond Colliders Study Group

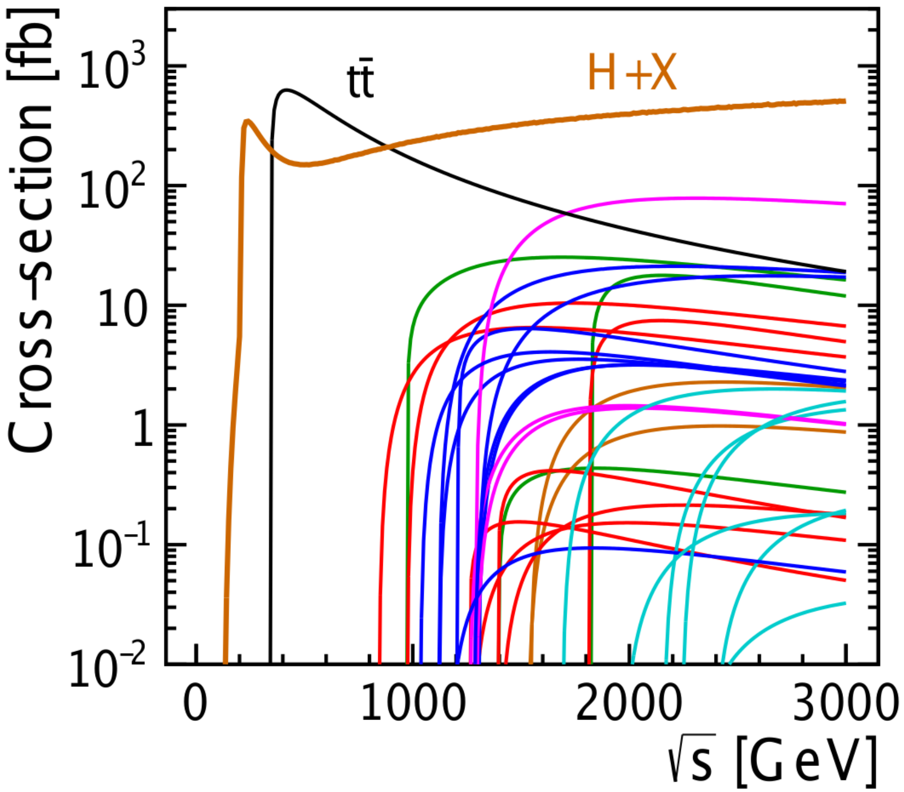
Important milestone: update of the European Strategy for Particle Physics (ESPP) to be completed in May 2020→ 10-year view has uncertainties beyond 2020 for the part of the programme other than LHC upgrade

Introduction to CLIC

CLIC is an international collaboration which is developing the technology and design for a multi-TeV range electron positron collider.



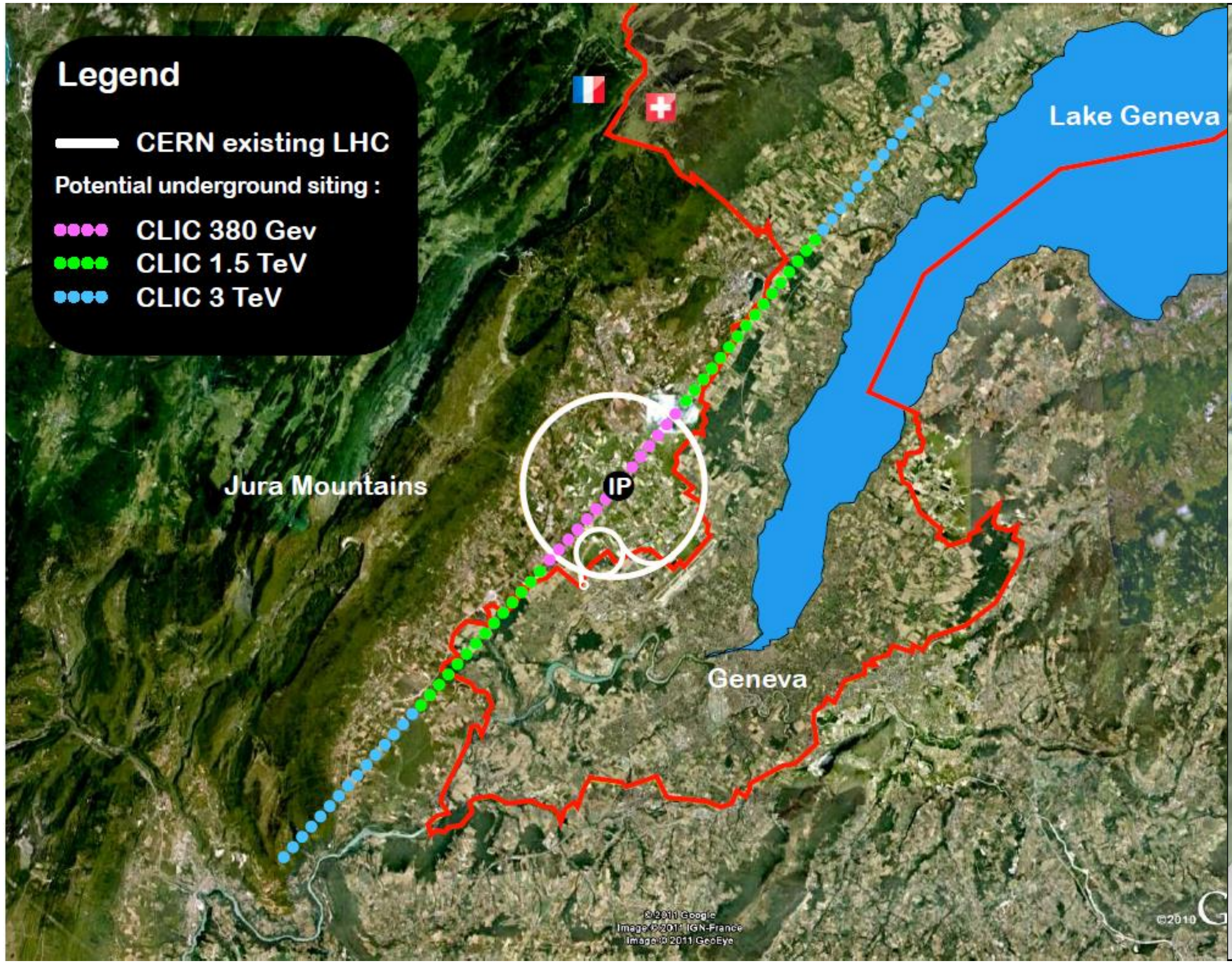
Standard model physics



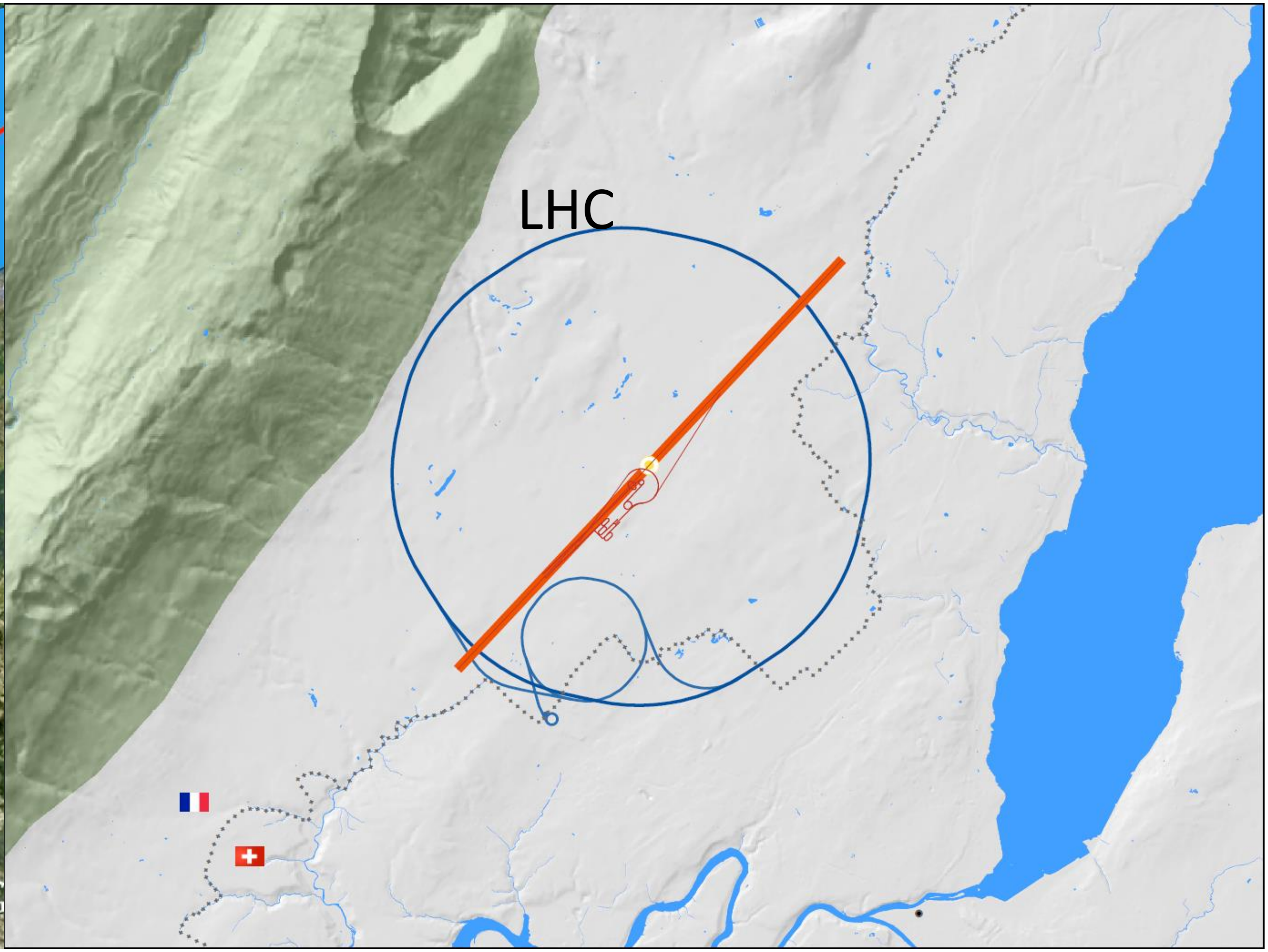
LHC must find!

Perhaps supersymmetry?

The CLIC accelerator at CERN



CLIC in stages up to 3 TeV



380 GeV initial energy stage

The CLIC collaboration

Accelerator collaboration approximately 50 institutes and the detector collaboration about 29.

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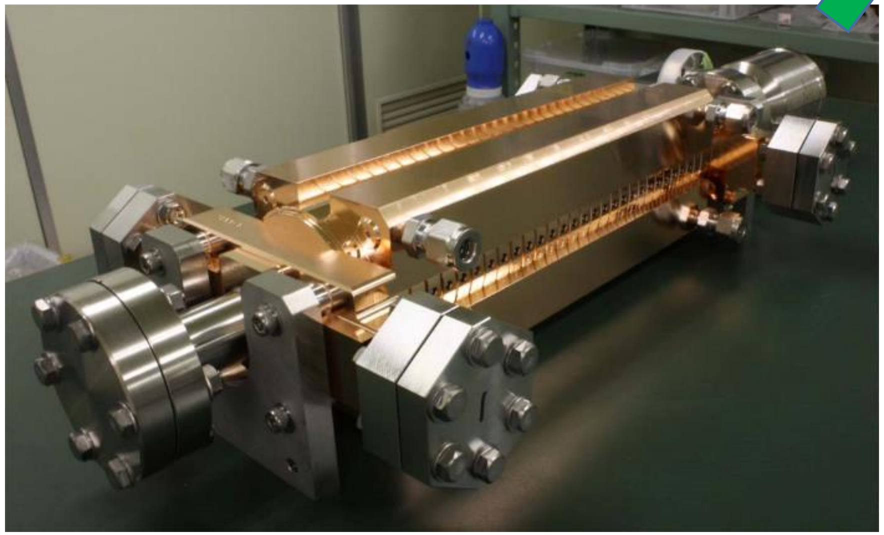
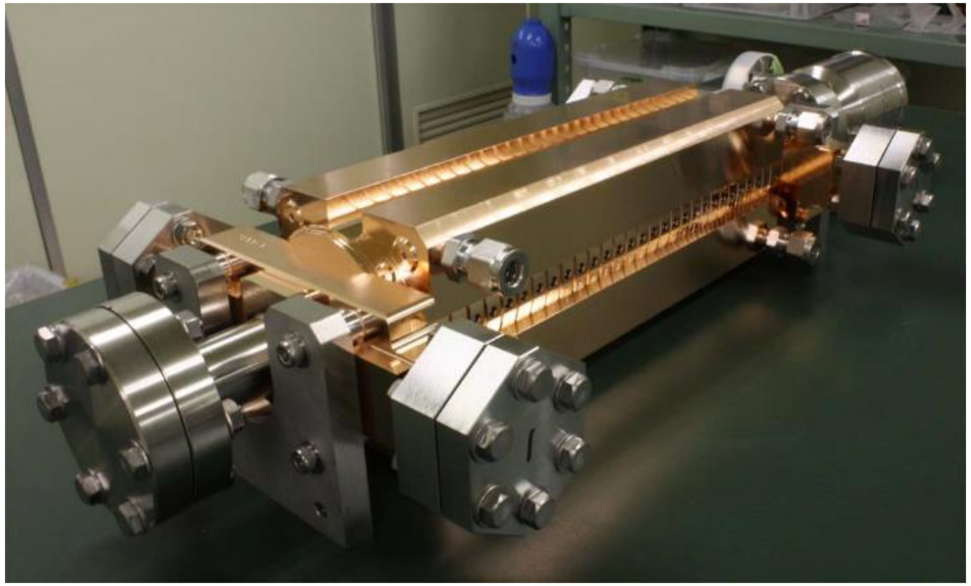
Key CLIC technology

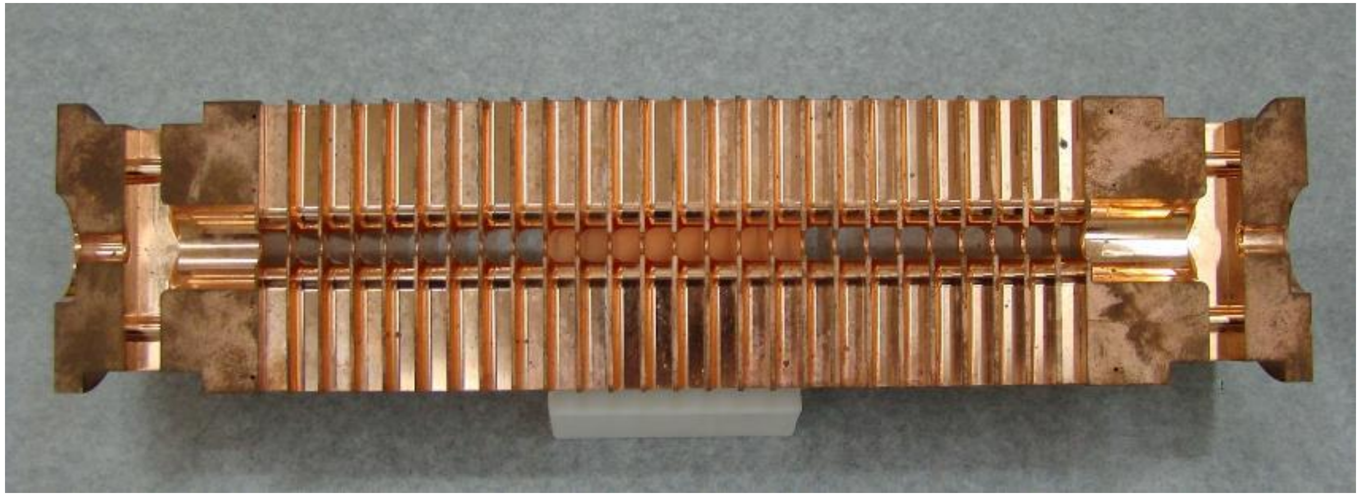


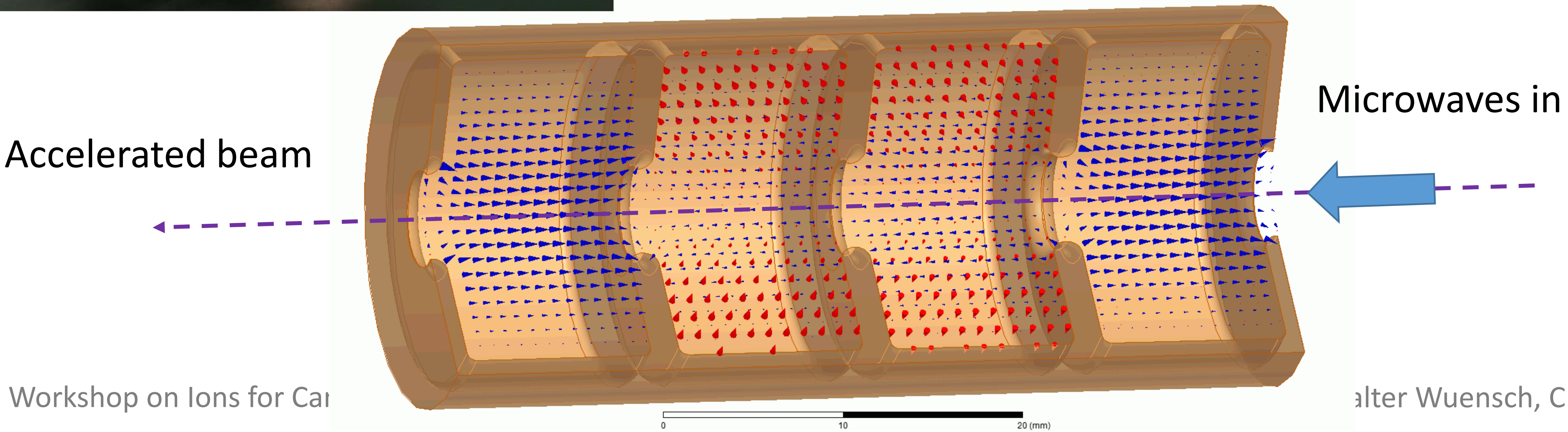
In order to reach multi-TeV e^+e^- collision energies the CLIC collaboration has invested significant effort to develop 100 MV/m gradient accelerating structures.

Existing linacs have gradients typically below 30 MV/m (SwissFEL, EuropeanFEL).

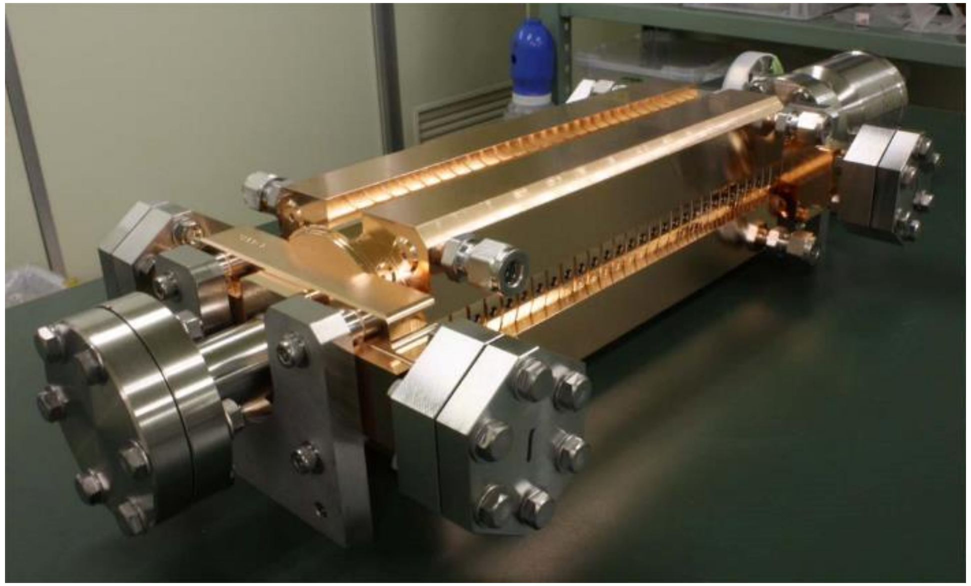
The basics of radio-frequency acceleration

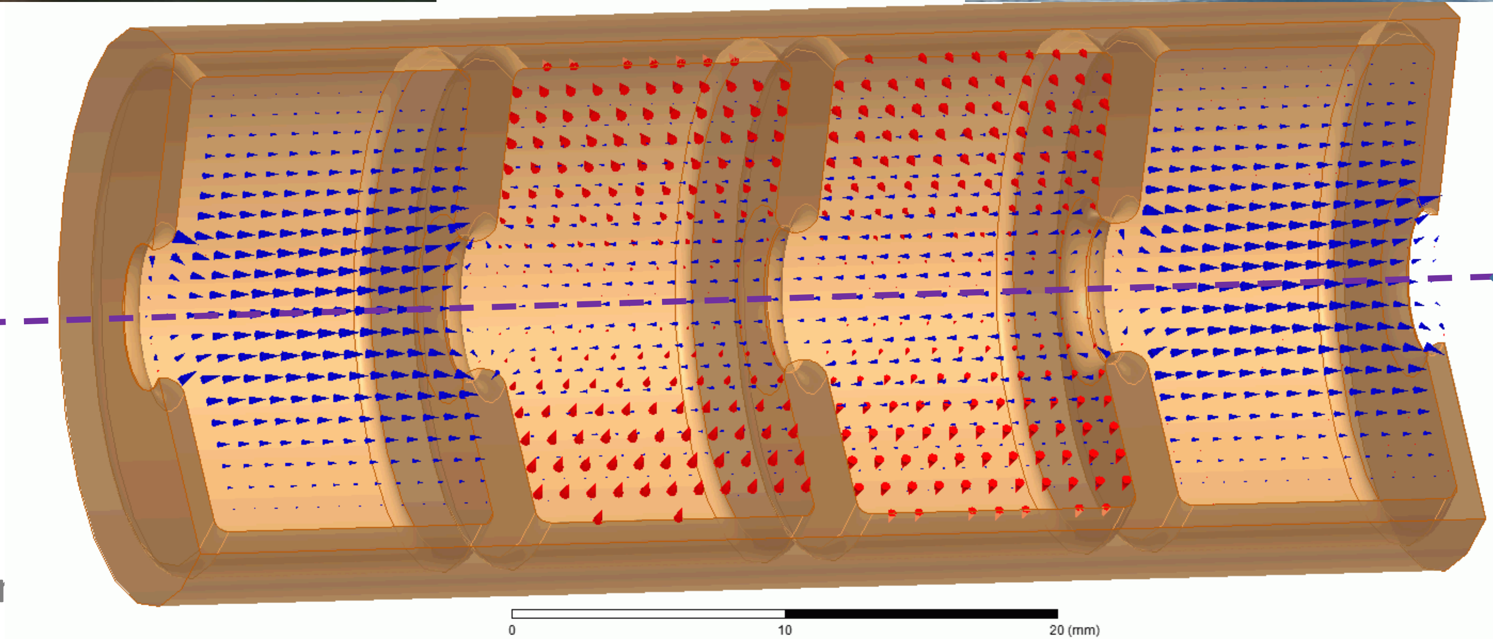






The basics of radio-frequency acceleration



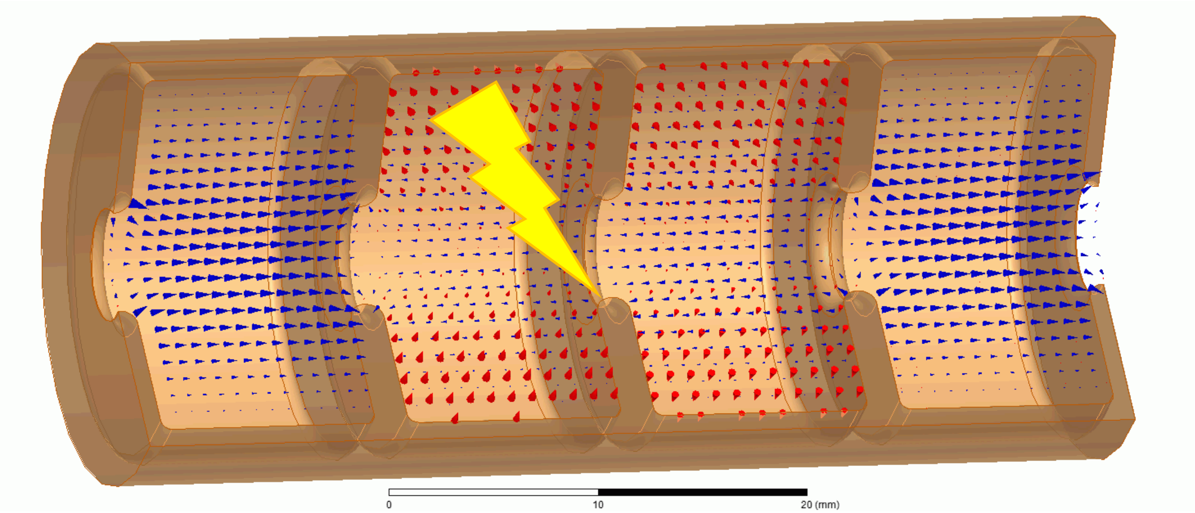


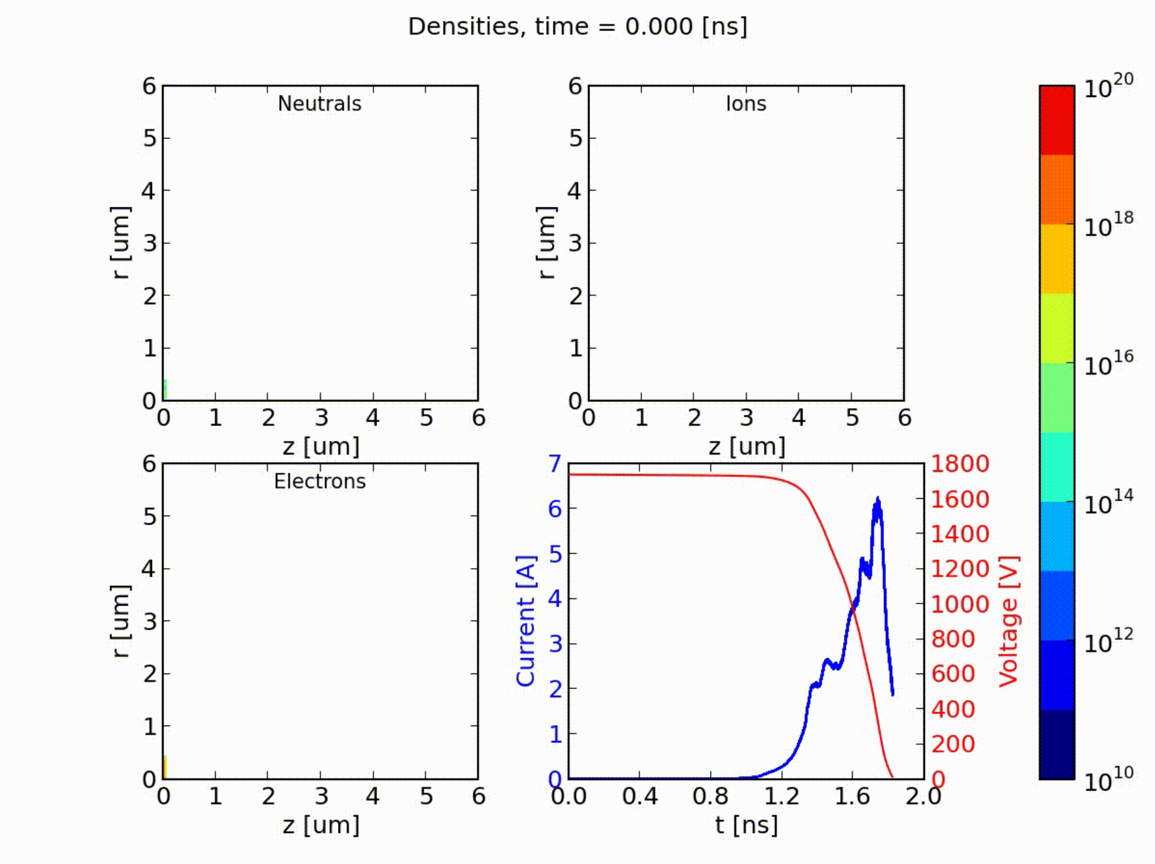
Microwaves in

Accelerated beam

Vacuum arcing

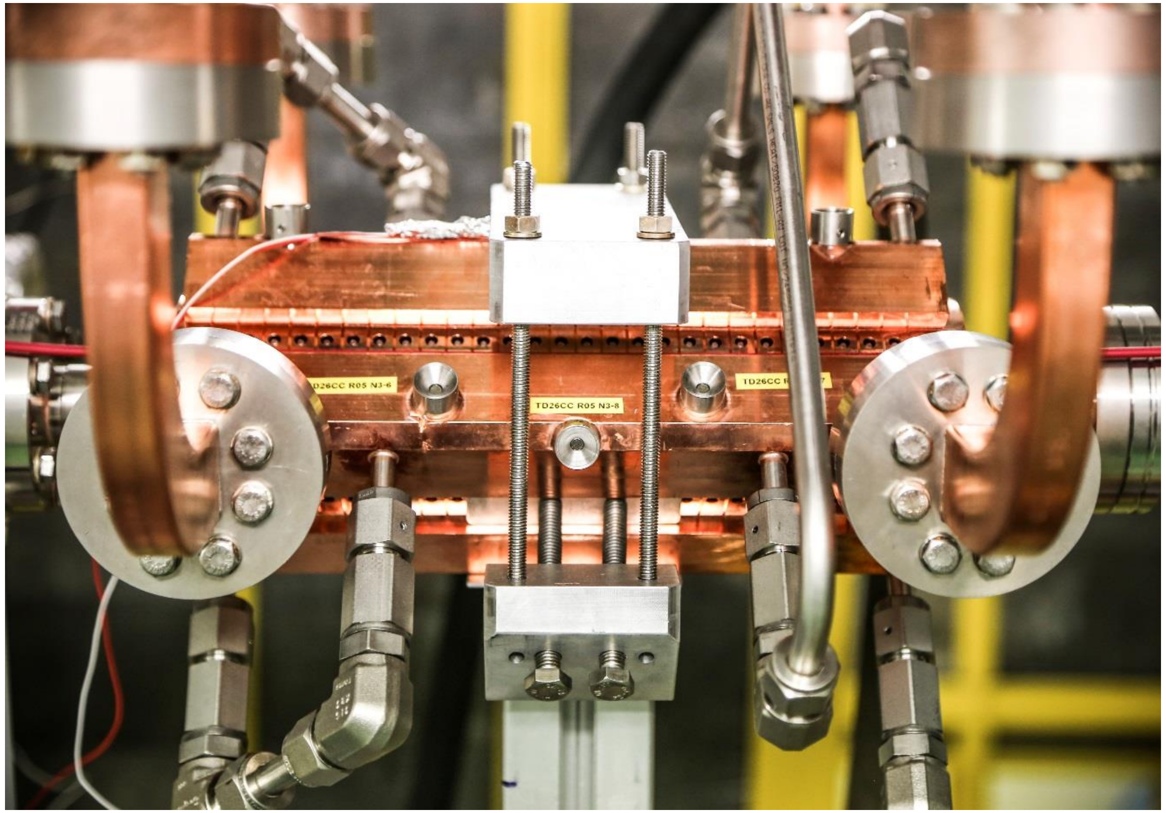
We have peak surface electric fields in excess of 200 MV/m.
Consequently one our main limitations is vacuum arcing, a.k.a. breakdown, which disrupts the beam.





Particle In Cell simulation of the onset of breakdown.

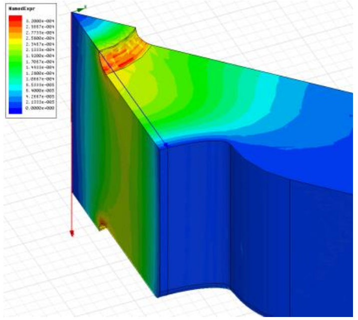
CLIC accelerating structures



25 cm

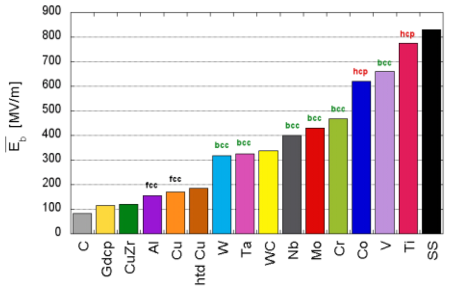
- 11.994 GHz, X-band
- 100 MV/m accelerating gradient
- Input power ≈50 MW
- Pulse length ≈200 ns
- Repetition rate 50-400 Hz

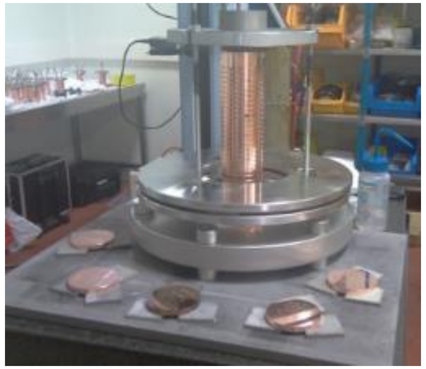
Micron–precision disk



$$S_c = \mathrm{Re}(\mathbf{S}) + \frac{1}{6}\mathrm{Im}(\mathbf{S})$$

$$BDR \propto e^{\frac{-E^f + \varepsilon_0 E^2 \Delta V}{k_b T}}$$



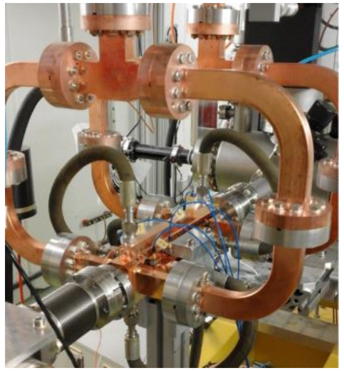


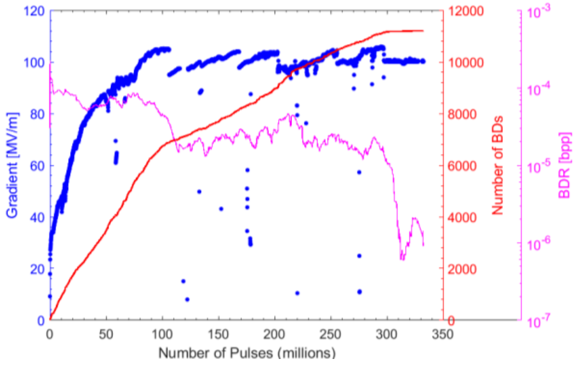
Fundamental physics of high fields on metal surfaces

High-gradient rf design

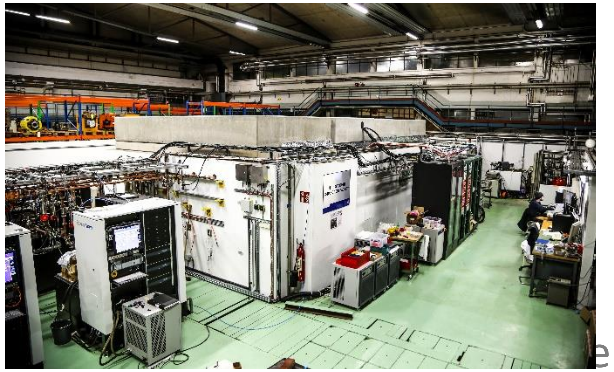
Fabrication of prototypes and technology optimization

High-gradient testing

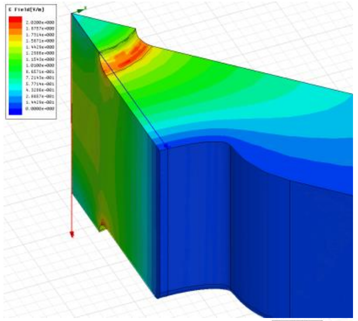




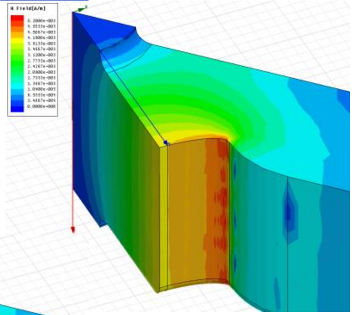
High-power test stands



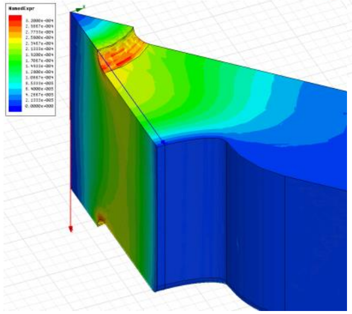
The effect of rf design



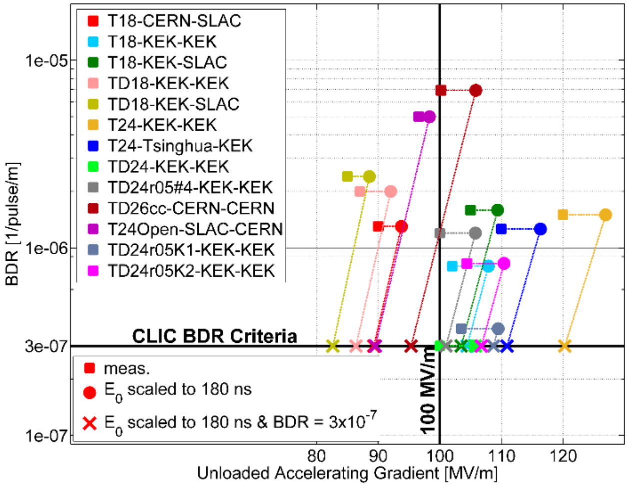
E_s/E_a



H_s/E_a



S_c/E_a^2



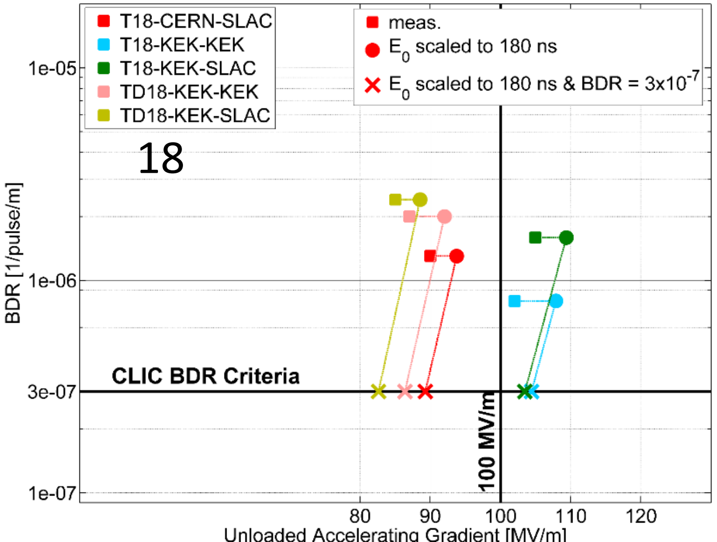
global power flow

$$\frac{P}{\lambda C} = \text{const}$$

local complex power flow

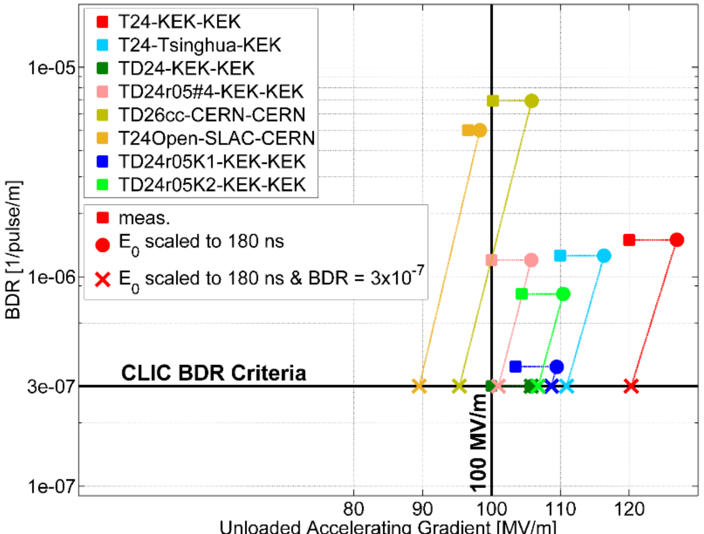
$$S_c = \mathrm{Re}(\mathbf{S}) + \frac{1}{6}\mathrm{Im}(\mathbf{S})$$

A. Grudiev, S. Calatroni and W. Wuensch, *New local field quantity describing the high gradient limit of accelerating structures*, Phys. Rev. ST Accel. Beams 12, 102001 (2009)



Initial design

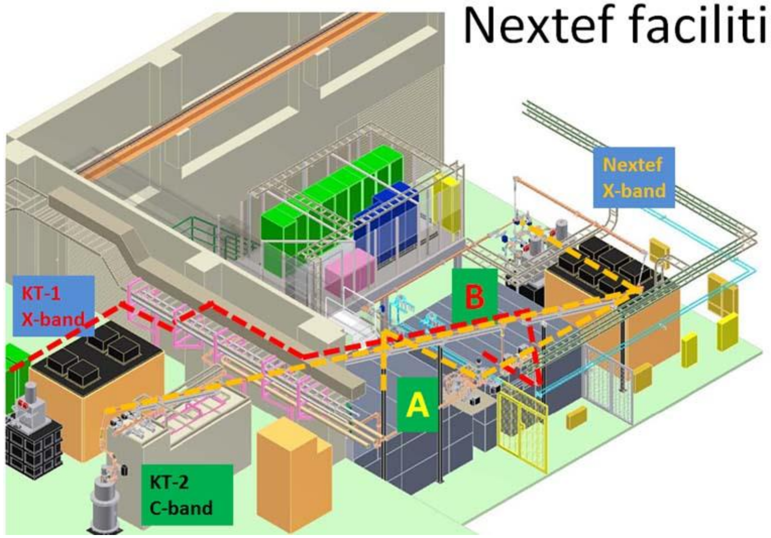
Later design

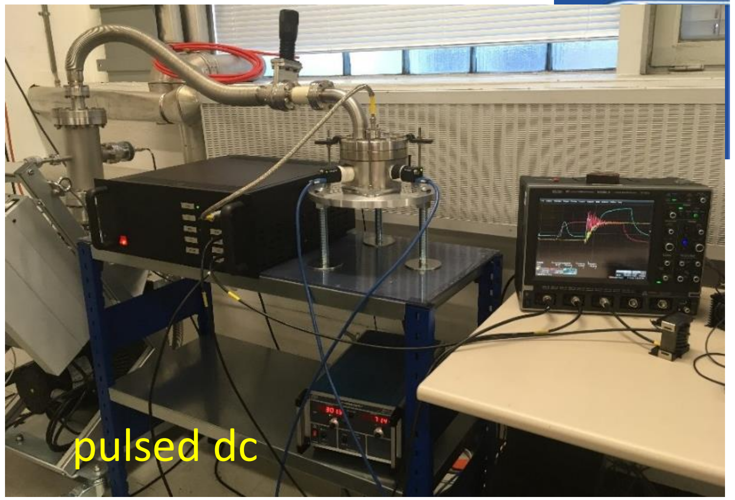


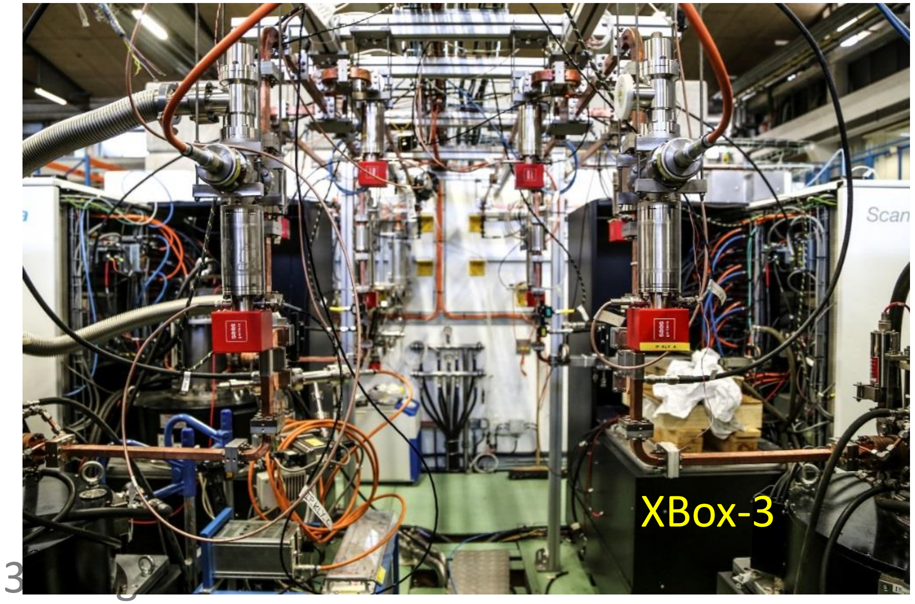
Where we do our experiments

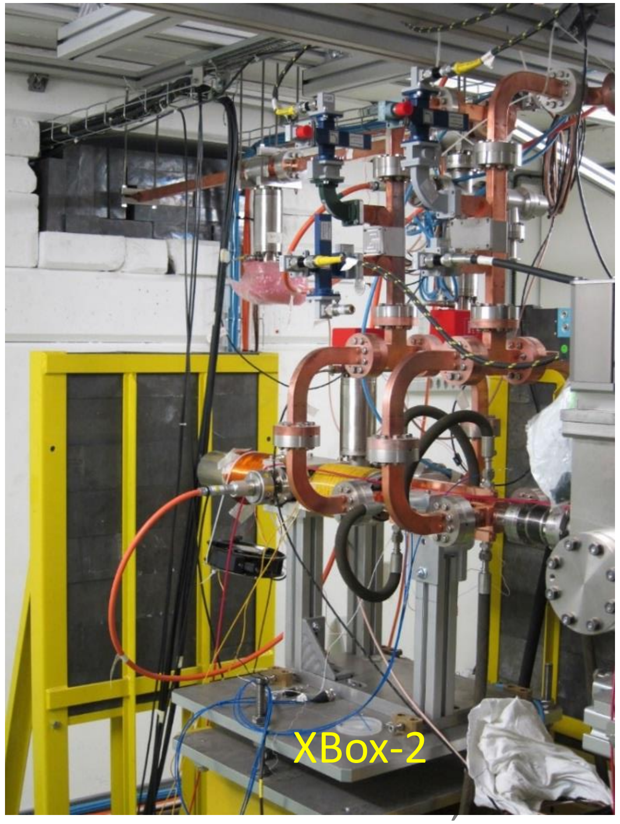
Klystron-based test stands at CERN:
- XBox1 to 3
- NEXTEF at KEK
- Two pulsed-dc systems.

Nextef facilities

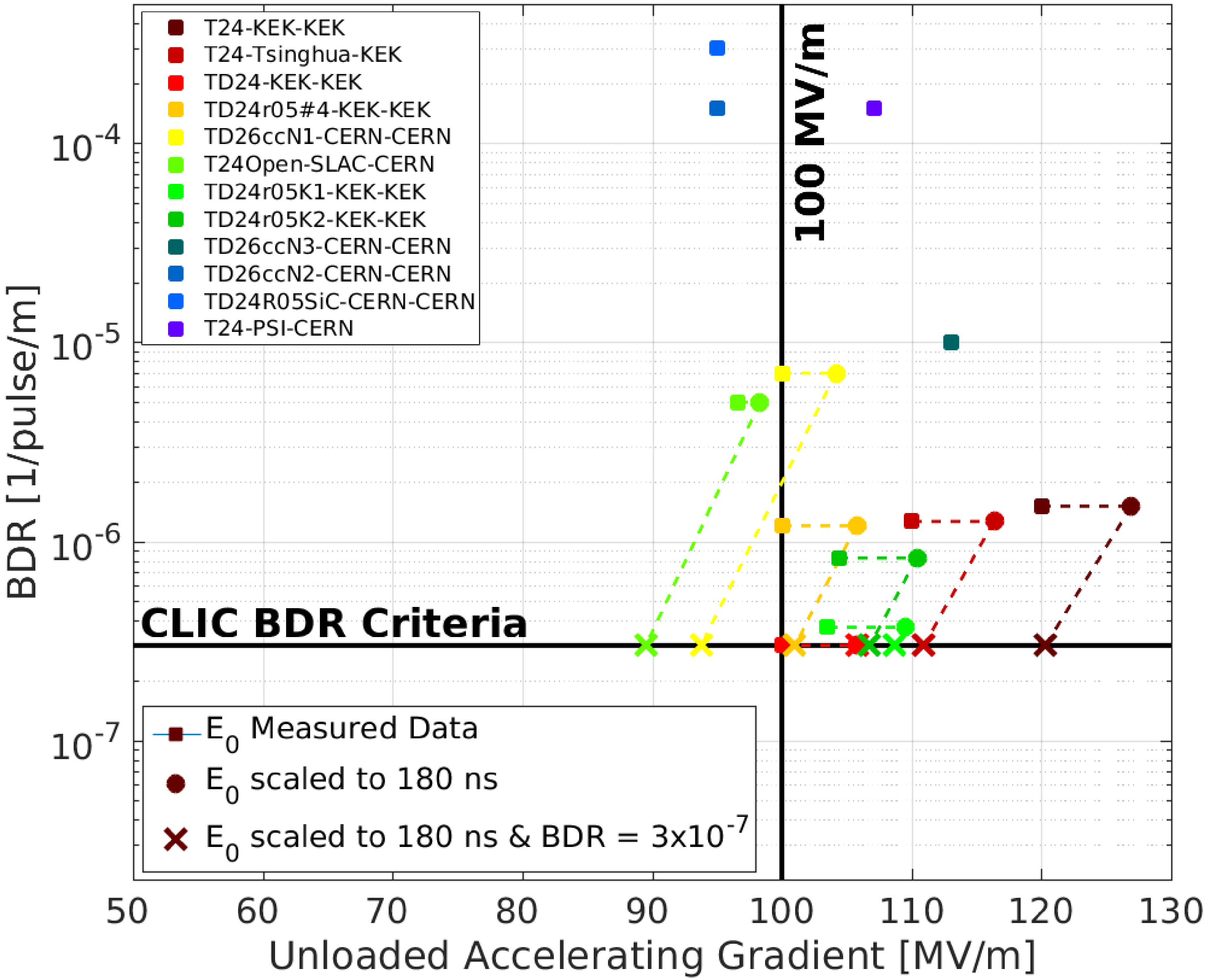








CLIC accelerating structures - performance summary



Currently under test:

XBox1 – TD26CC N2

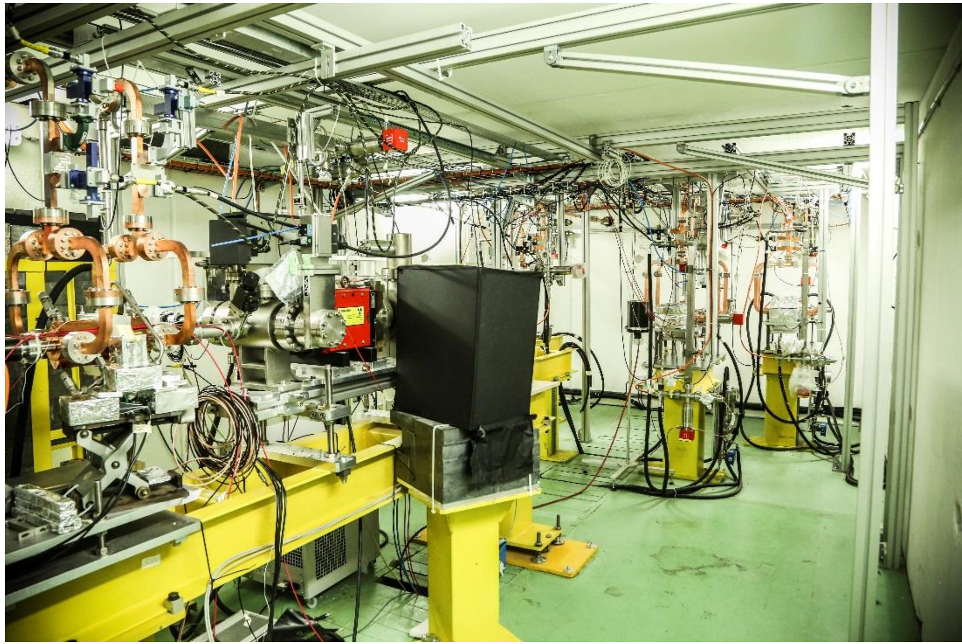
XBox2 – TD26CC N3

XBox3 – TD24CC SiC

T24 PSI

SBox - 3 GHz BTW

NEXTEF (KEK) – TD24 R05 K2



Applications of high gradient beyond high-energy physics

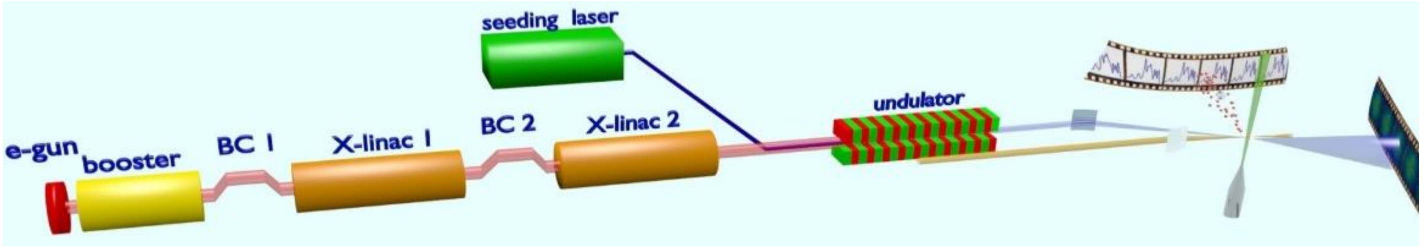
Beam manipulation and diagnostics:
Energy spread linearizers and deflectors

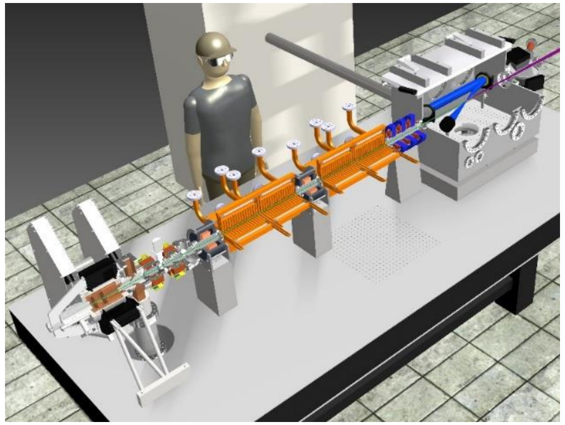
Thompson/Compton scattering source

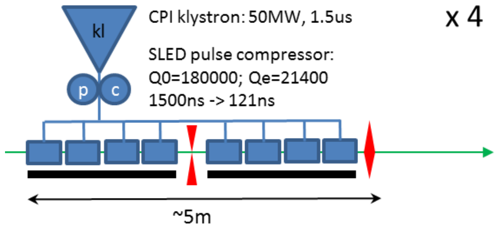
XFEL

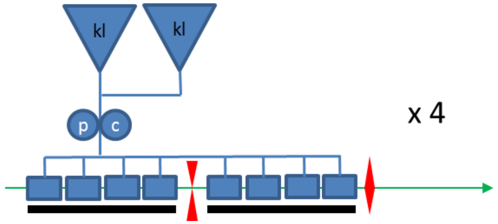
Medical

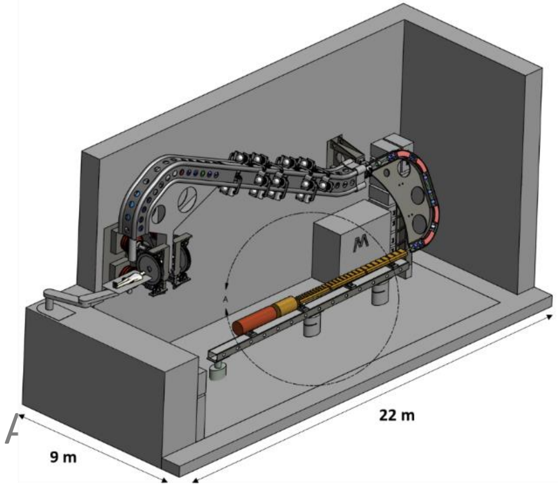
Advanced acceleration

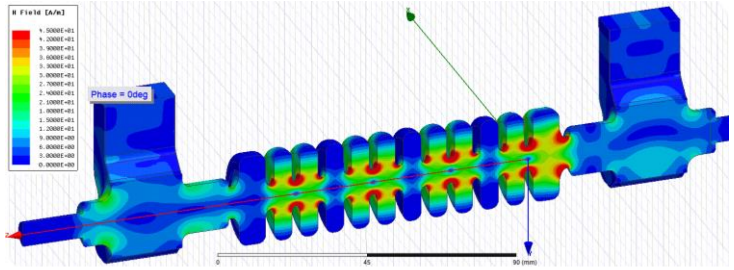












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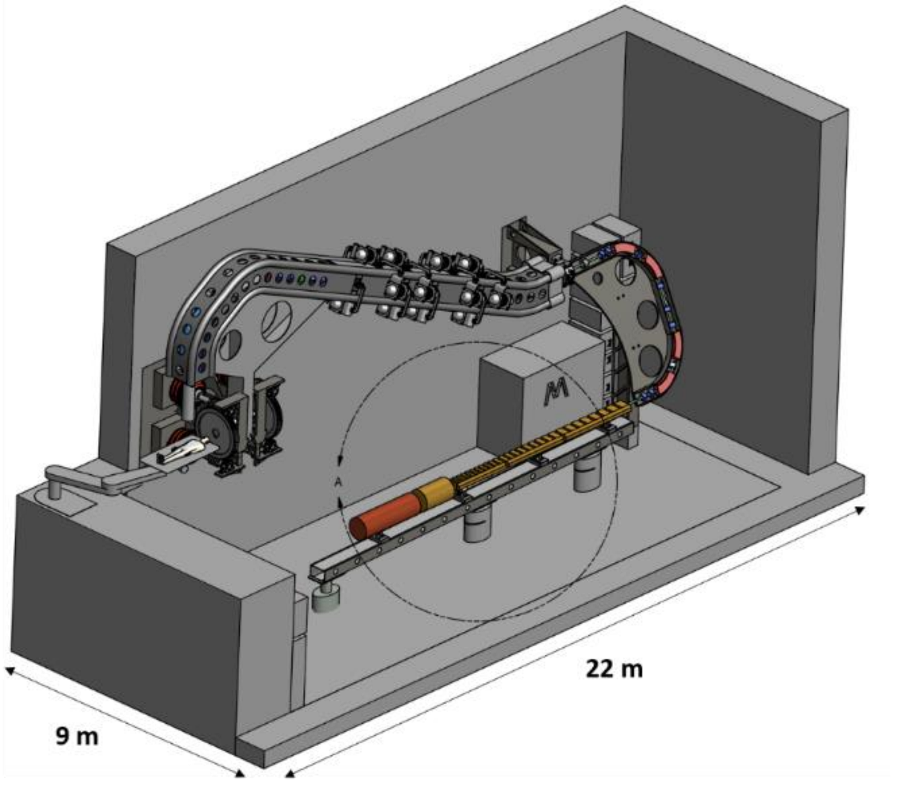
Applying CLIC technology to medical accelerators

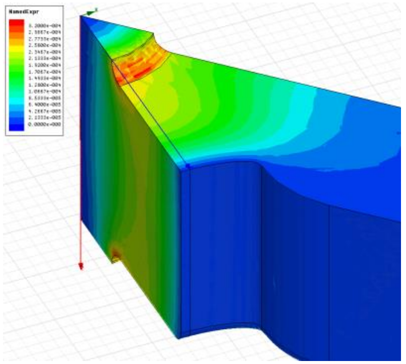
- There are a number of initiatives to develop linac-based proton and ion treatment facilities.
- Already some years ago the CLIC high-gradient team was approached by Ugo Amaldi to jointly study applying the know-how for high-gradient accelerators to medical linacs
- A group of us received CERN KT (Knowledge Transfer) fund support to design and build a prototype structure, to show the potential of the CLIC technology in this domain. I will now describe some highlights of this effort.

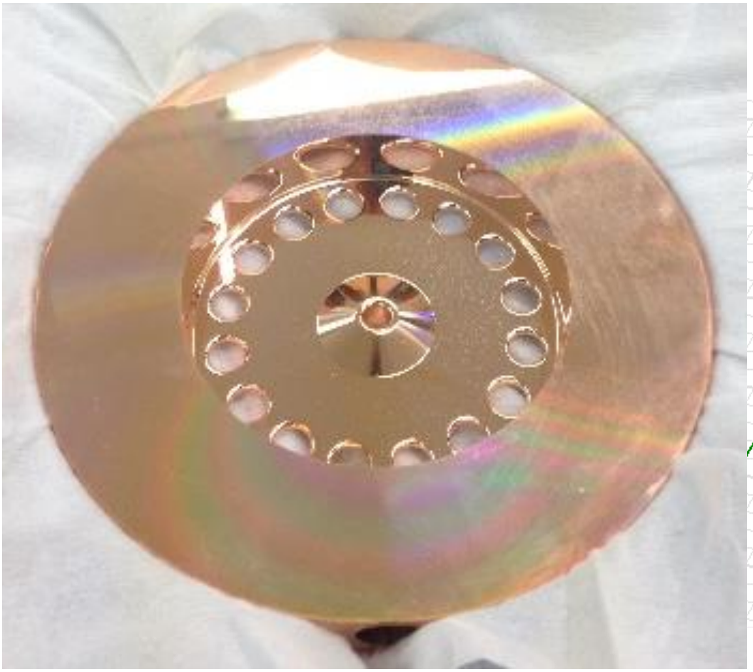


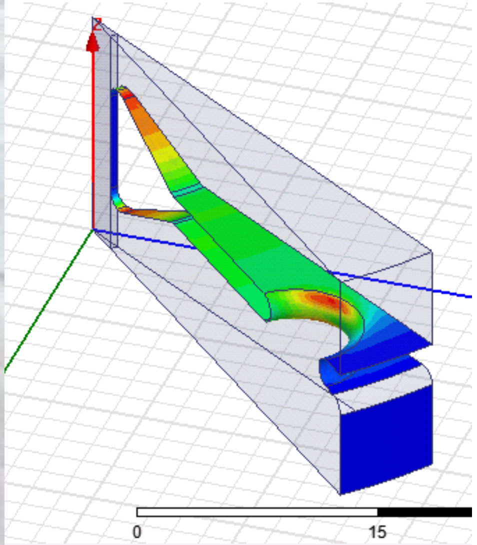
TULIP – an example of a high-gradient linac based single room proton treatment facility.

What's the ~~problem~~ challenge?

Our electron linac technology is for particles moving near the speed of light.
Protons and ions in a medical linac need to be accelerated when they are still moving slowly, in the range of half the speed of light.



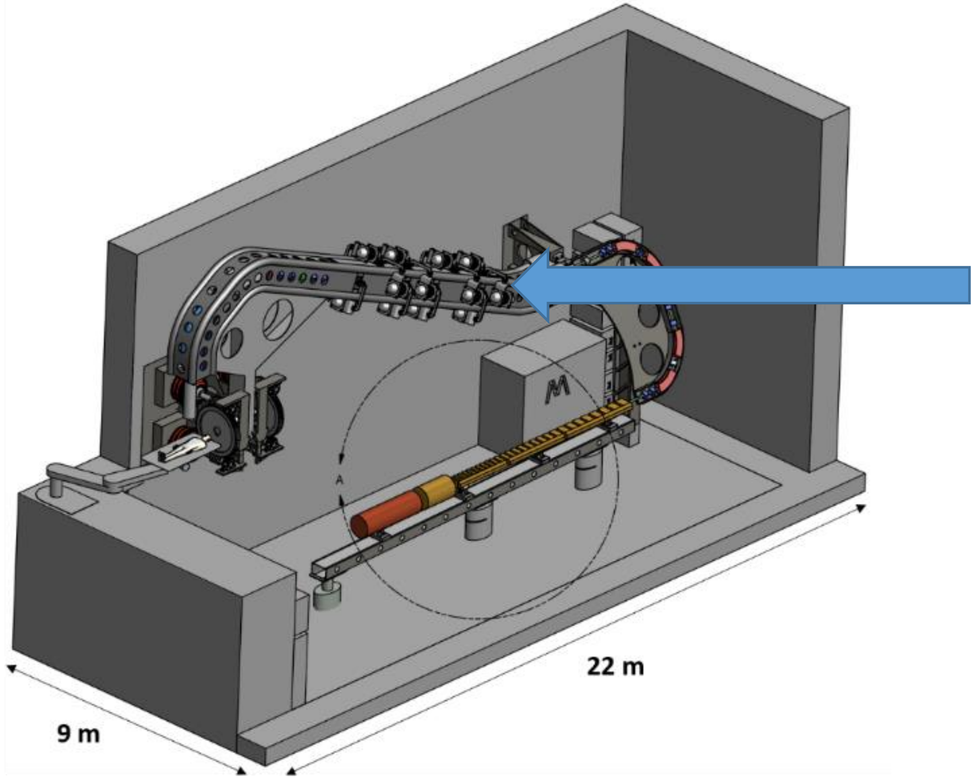


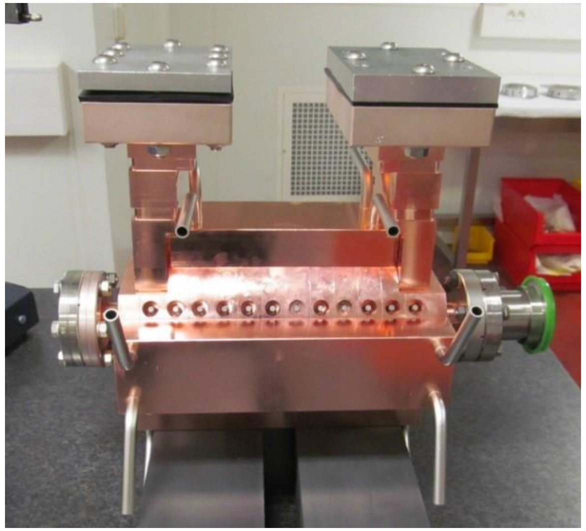


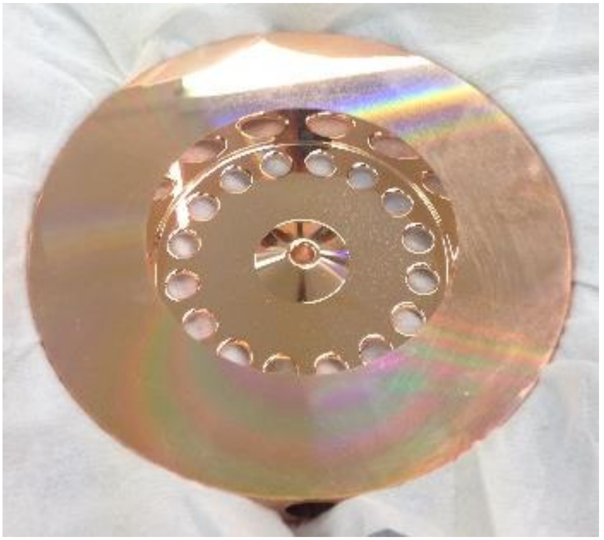
For relativistic electrons/positrons, β=1:
100 MV/m

For β=0.38:
50 MV/m
Hard to extend this to lower β, higher is easy.

The TULIP example

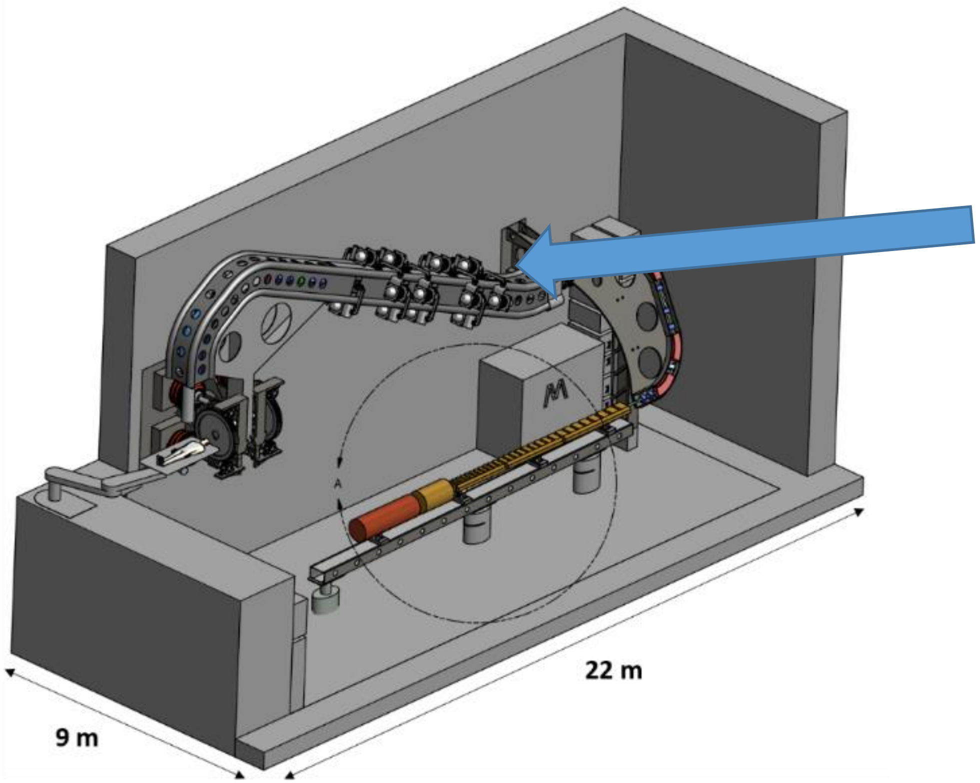


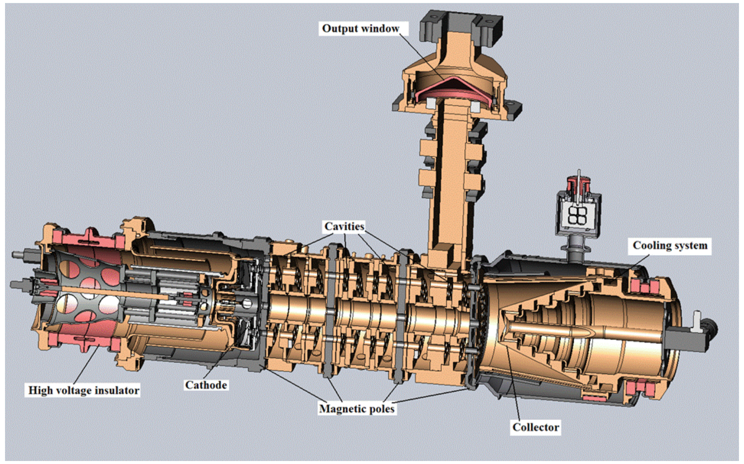


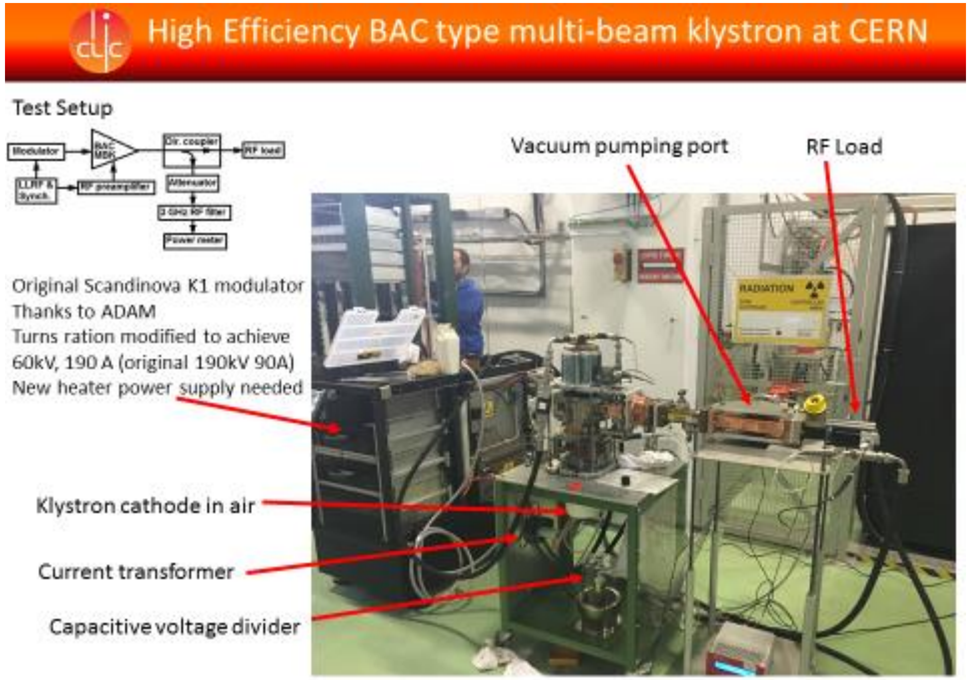


By applying CLIC high-gradient technology we can raise the accelerating gradient from the <20 MV/m in LIGHT to 50 MV/m, for example making single room facilities possible.

Additional element: High-efficiency power source

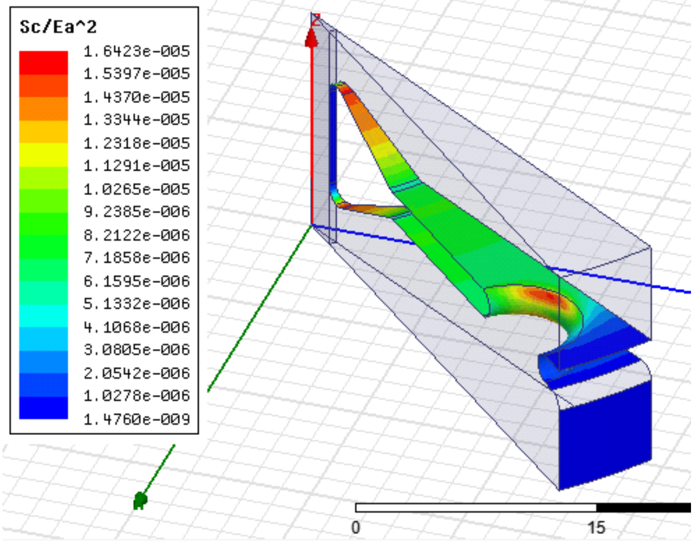


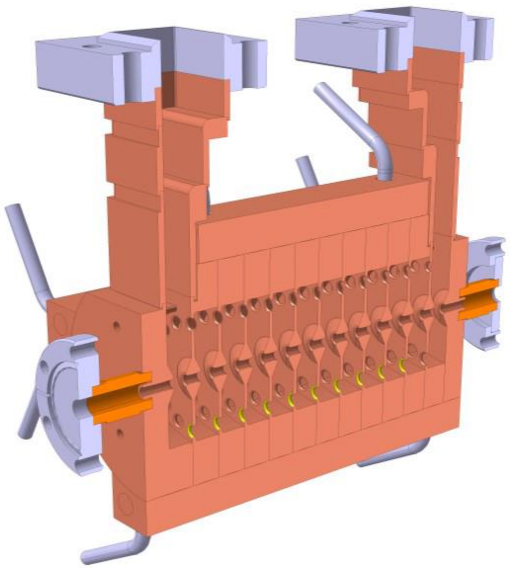


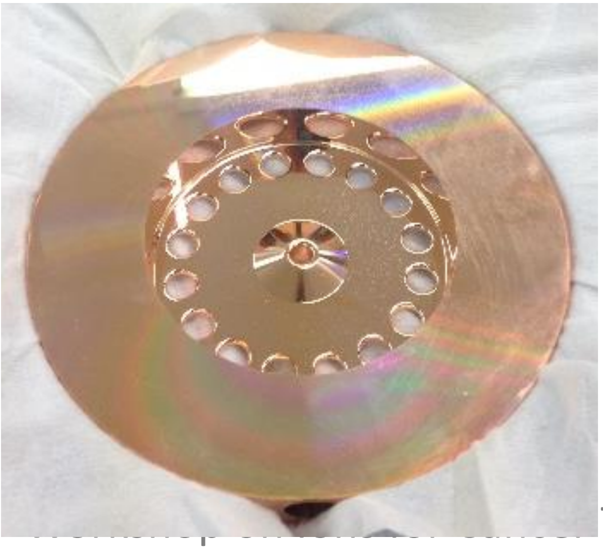


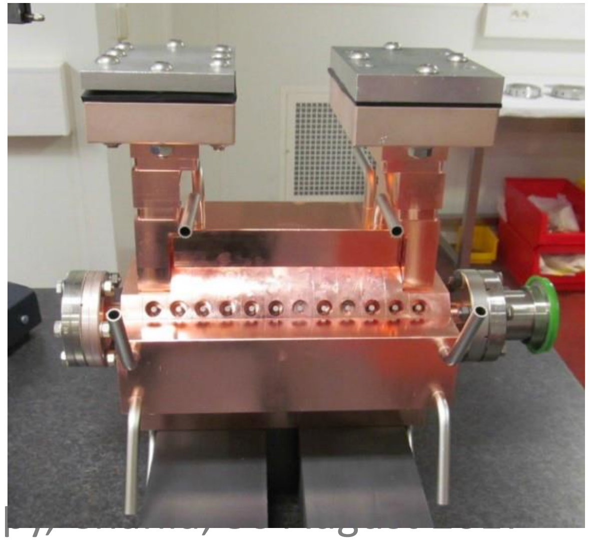
Radio-frequency power source efficiency is also a crucial issue for CLIC.
3 GHz, > 60% efficiency, 70 kV klystron built by VDBT.
Has potential to reduce investment and operating cost.

But does it work as well as we expect?



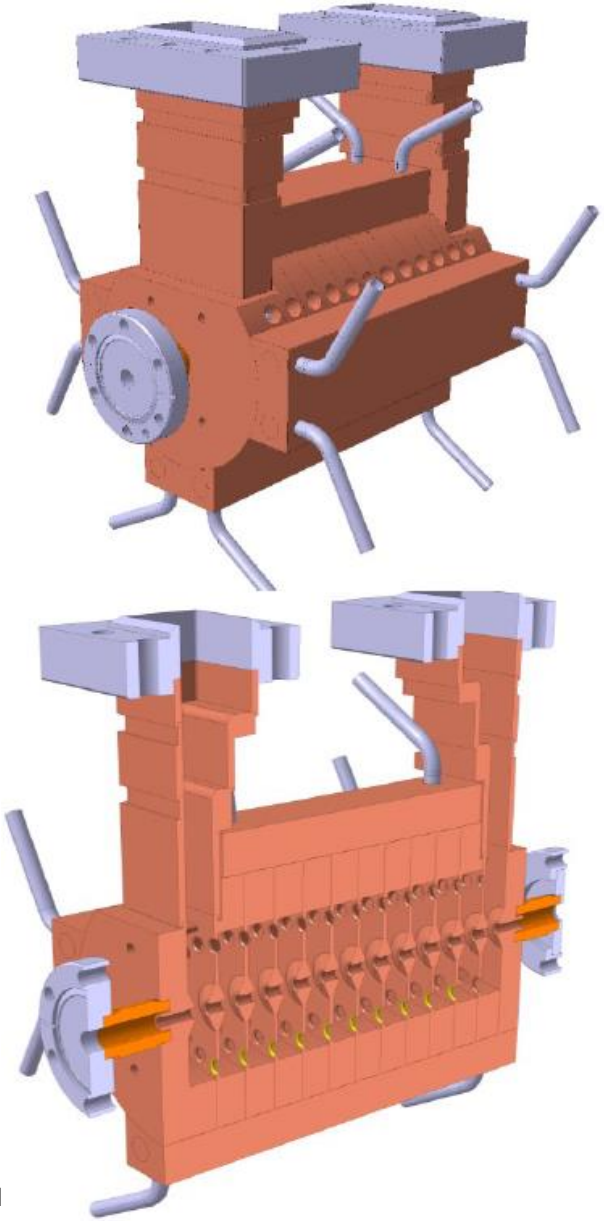






- CERN KT fund accepted our application for funding to build two such structures based on CLIC design, fabrication and operation technology.
- CLIC study members designed and are testing the structures (we get important data on high-gradients from these tests).
- Two have been built and the first is under high power test.

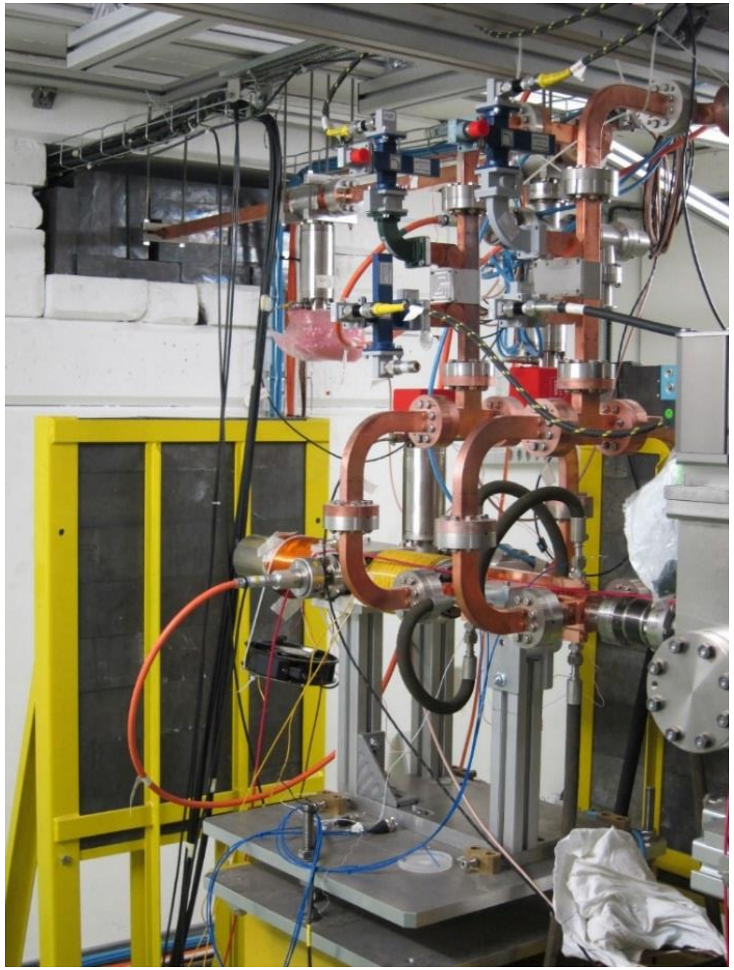
Backward Travelling Wave (BTW)

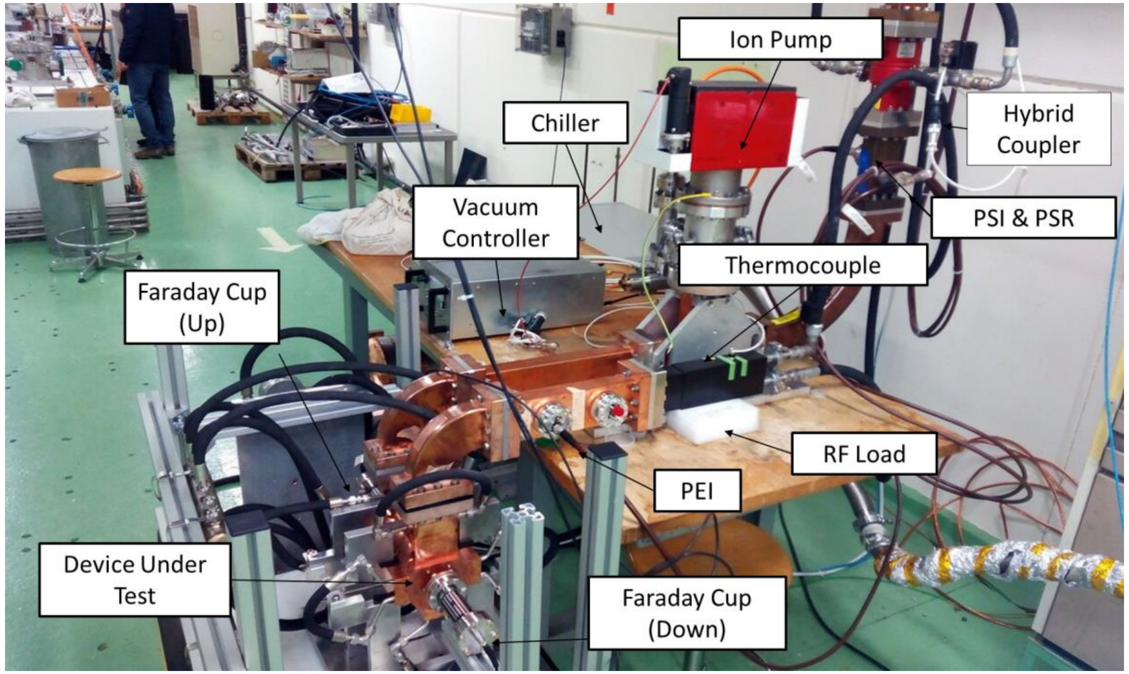


- novel HG accelerating structure designed to reach an accelerating gradient of **50 MV/m** for proton (TULIP project);
- 2.9985 GHz mode with 5π/6 phase advance;
- the small iris aperture guarantees the low group velocity required to achieve HG.

Number of RF cells	12
Geometric β – RF Ph. Adv.	0.38 – 150 deg
Total length	189.84 mm
Max Sc/Ea^2	0.29 mA/V
Max Es/Ea	3.9
Pin @ 50 MV/m	20.16 MW
Pout @ 50 MV/m	11.24 MW
Filling time	220 ns
Group velocity (first/last)	0.39 / 0.21 %c

High-gradient testing

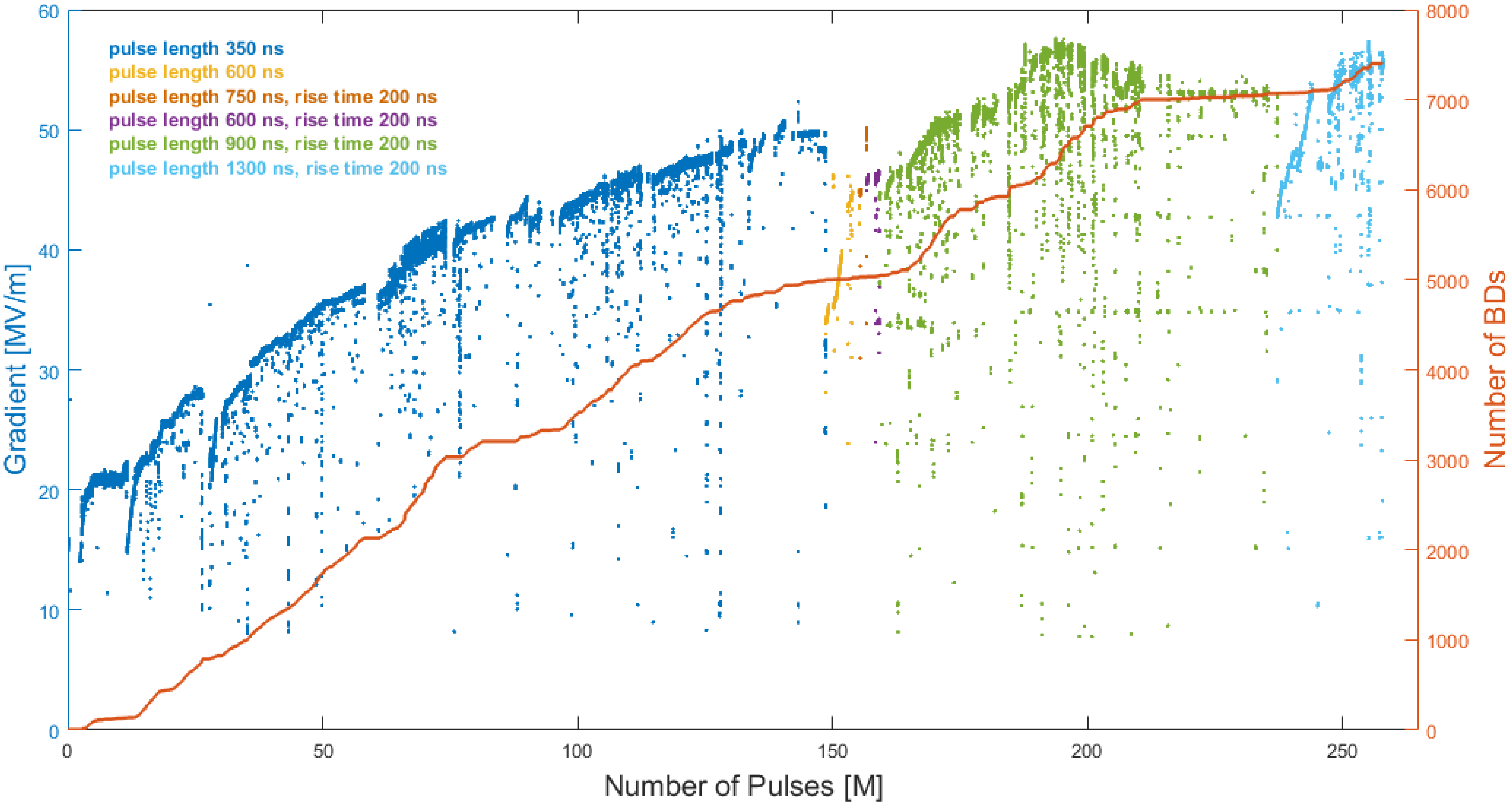




We have adapted and used experience, diagnostics, software and algorithms from the CLIC high-gradient program.

Conditioning status of the high-gradient medical linac structure

50 MV/m



High-gradient resource

Most recent workshop on high gradients:
https://indico.cern.ch/event/589548/

Inspiring further developements

MANCHESTER 1824

Lancaster University

The Cockcroft Institute of Accelerator Science and Technology

The Christie

CERN

PROBE: PROTON BOOSTING EXTENSION FOR IMAGING AND THERAPY

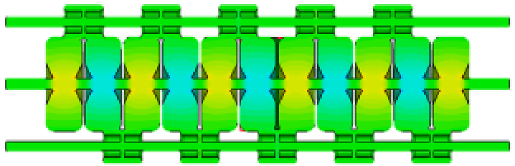
Sam Pitman
Dr Graeme Burt
Dr Hywel Owen

CERN · Lancaster University · The Cockcroft Institute · MANCHESTER 1824

FINAL STRUCTURE

- 3 GHz- S-Band
- Side coupled 54MV/m
- Aggressive gradient limits
  - Epeak < 200MV/m
- Thin septum (2mm)
- π/2 mode
- 11 cell prototype cavity
- β=0.59

Parameter	Units	S-Band SCSWS
Phase adv.	[deg]	90
Cell Length	[mm]	29.8
Coupling Factor	[%]	2.16
Rs/L	[MΩ/m]	76
$\sqrt{Sc}$/Eacc	[$\sqrt{W}$/MV]	2.4e-2
Eacc	[MV/m]	54
Hpk	[kA/m]	254
Epk	[MV/m]	200



radiabeam SYSTEMS

10th International workshop on high-gradient acceleration, Valencia, Spain

High-gradient low-β structure based on acceleration with the first negative spatial harmonic

Sergey V Kutsaev

June 15, 2017

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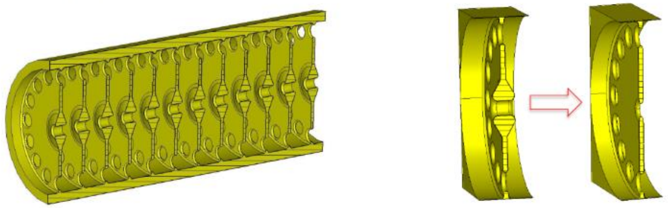
Grant, Proposal No. 0000219678 and STTR grant DE-SC0015717

Low beta structure for ACCIL

radiabeam SYSTEMS

- We used CERN TULIP backward travelling wave (BTW) as a reference*



- We found that at β~0.4, the required peak surface field is ~200 MV/m to sustain 50 MV/m accelerating gradient
  - Reducing these fields lead to 160 MV/m lead to a significant shunt impedance drop
- Different approach is required for β=0.3 section

* S. Benedetti, A. Degiovanni, A. Grudiev et al., Proceedings of LINAC2014, Geneva, Switzerland.

Conclusions

- Technology developed for high-energy physics can provide a significant performance improvement for medical hadron linacs.
- We hope to continue to work with your community to have this improvement make an impact.

Acknowledgements: I would like to sincerely thank all my colleagues from CLIC high-gradient, TERA foundation and EPFL, the CERN KT group, University of Valencia, OMA for all their contributions.