



High-gradient rf: development and applications

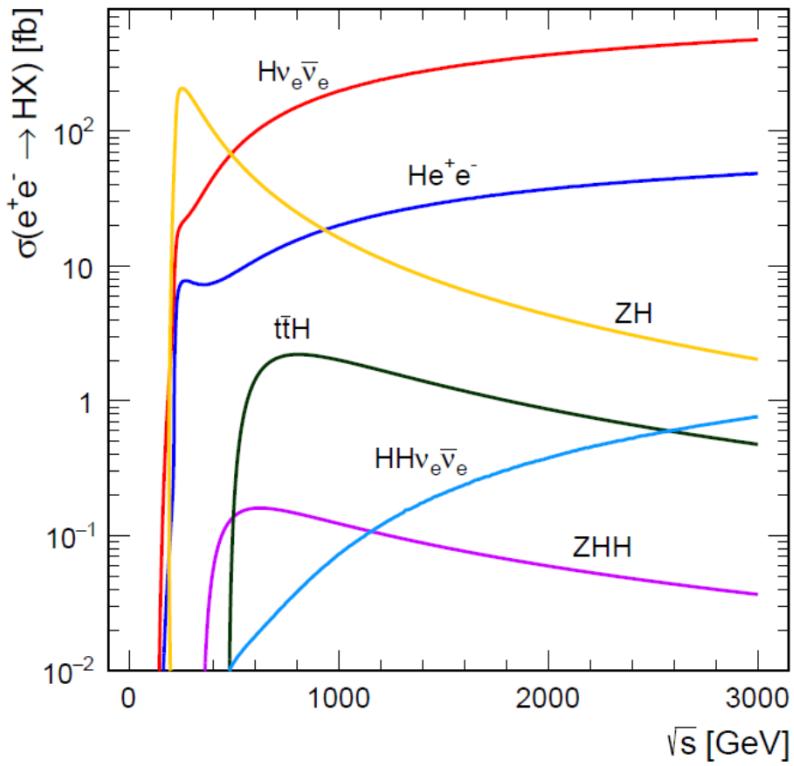
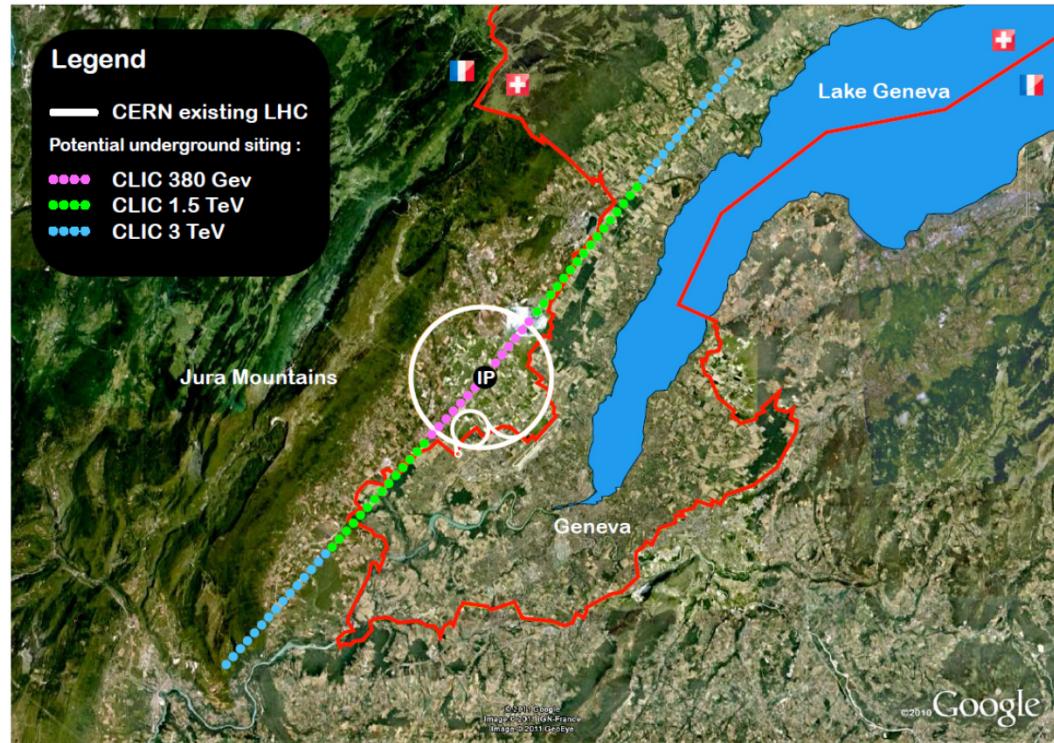


Background – CLIC collaboration

The CLIC e^+e^- linear collider targets multi-TeV energies, to be approached in stages:

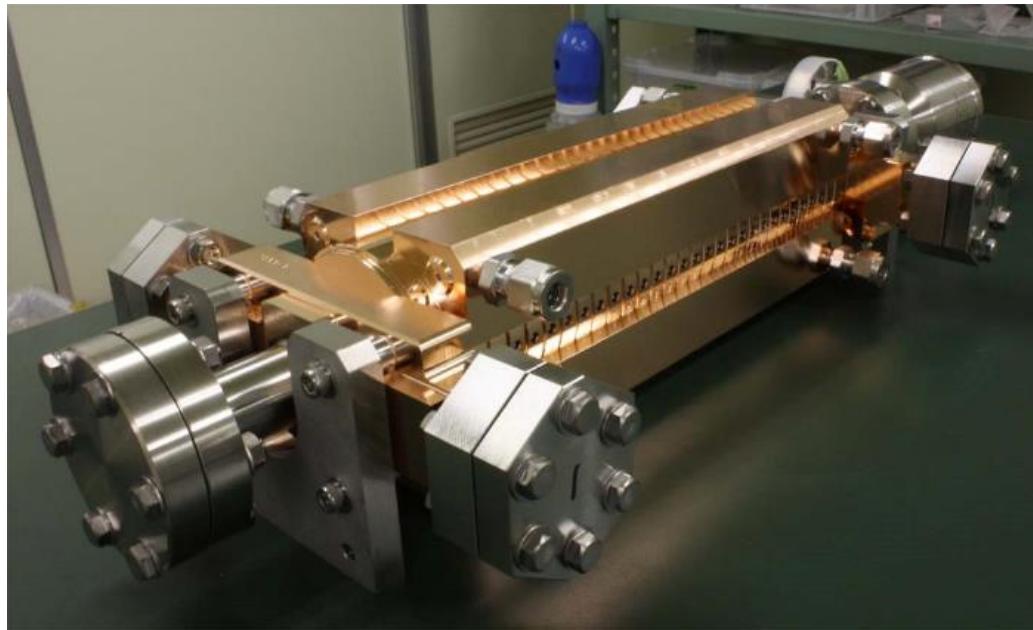
Higgs and top first at 380 GeV, then on to multi-TeV based on new LHC discoveries.

For energy reach in a timely fashion, the CLIC collaboration has made a major effort to push normal conducting acceleration up to 100 MV/m.



Outline

- Highlights from the CLIC effort to achieve high gradients by pushing normal conducting rf technology.
- Survey of some applications which may benefit from these high-gradient developments.



Prototype X-band, 12 GHz, CLIC accelerating structure



Part I: The high-gradient development program



The development

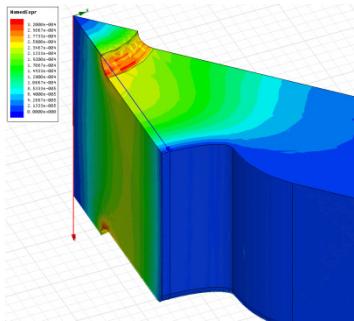
Due to the importance of gradient for a linear collider, we have had the opportunity to carry out an approach:

- Broad – Include all aspects theory, technology, testing
- Systematic **think/test/understand/try again** not always an option for projects. **Lots of learning from failures!**

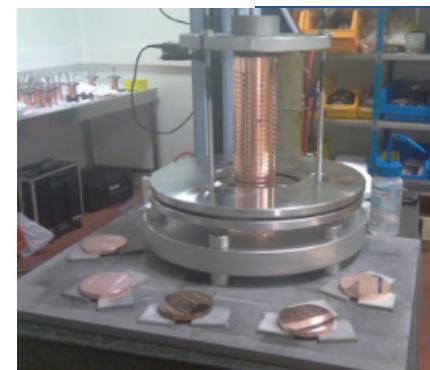
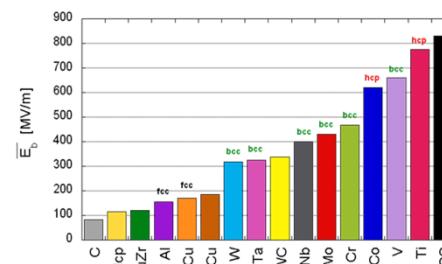
Starting point for CLIC collaboration work described here is end of 30 GHz era of CLIC and end NLC/JLC project.

Now an attempt at an overview





$$BDR \propto e^{\frac{-E^f + \epsilon_0 E^2 \Delta V}{k_b T}}$$

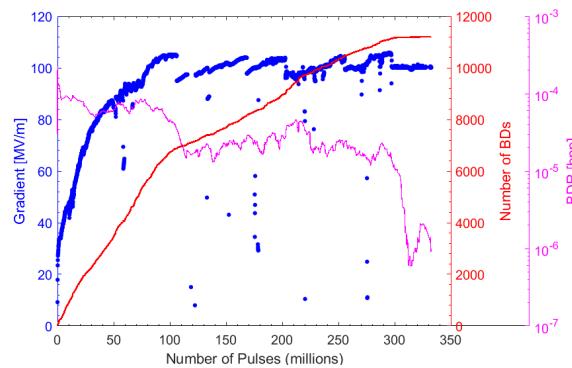
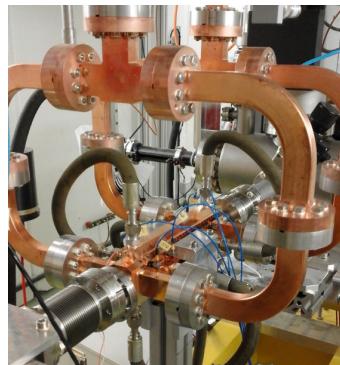


$$S_c = \text{Re}(S) + \frac{1}{6} \text{Im}(S)$$

High-gradient rf design

Fundamental physics
of high fields on metal
surfaces

Fabrication of
prototypes and
technology
optimization



High-gradient testing

High-power test
stands



October 2016

, CERN

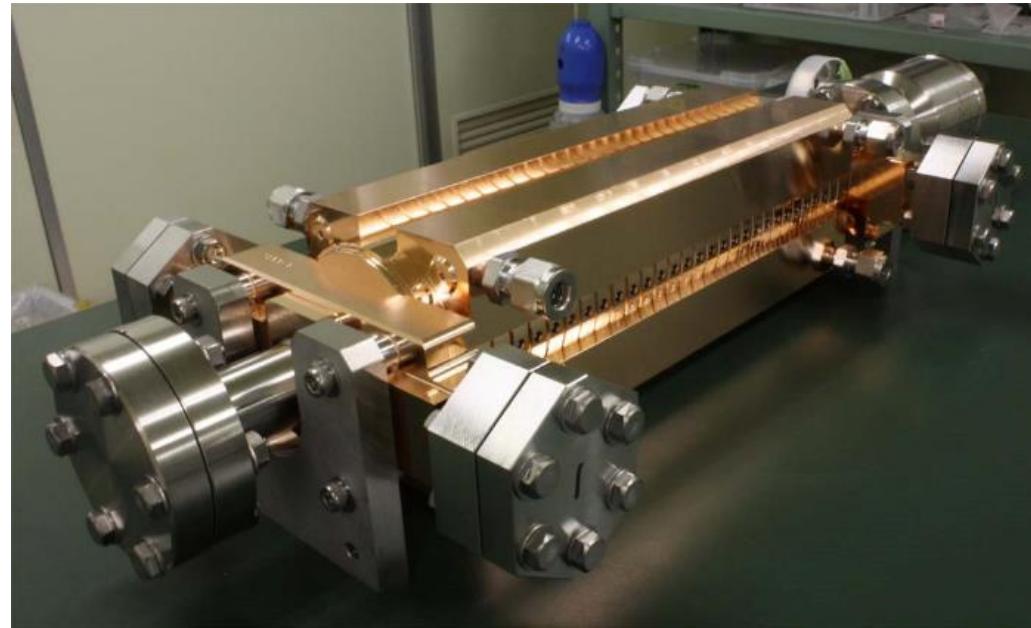


CLIC accelerating structure



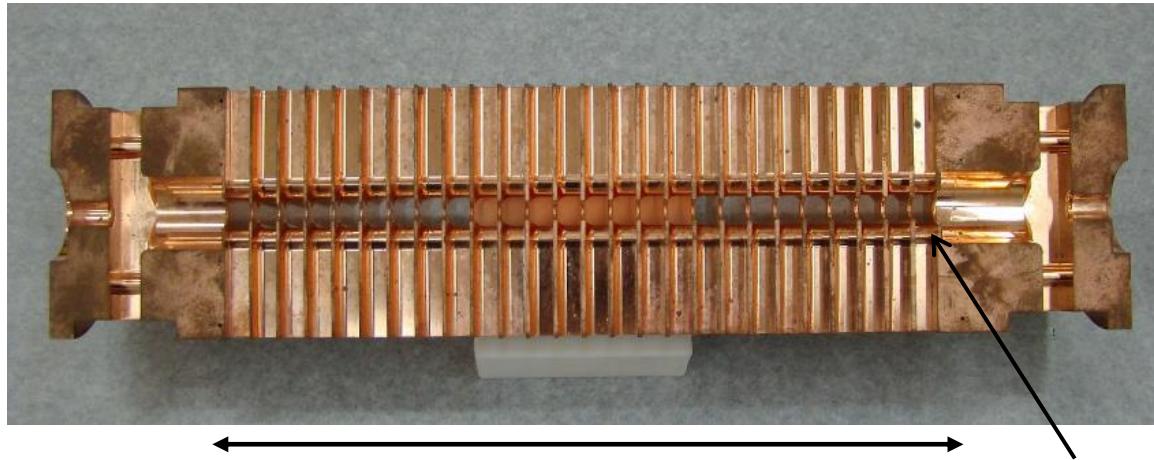
Outside

11.994 GHz X-band
100 MV/m
Input power \approx 50 MW
Pulse length \approx 200 ns
Repetition rate 50 Hz



HOM damping waveguide

Inside

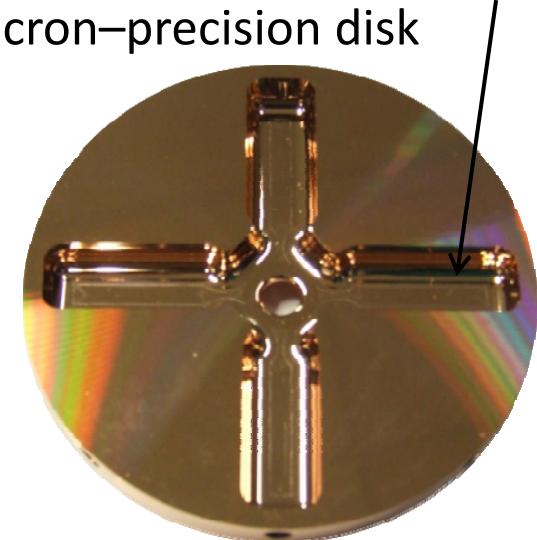


25 cm

LINAC16, East Lansing, 27 September 2016

6 mm diameter
beam aperture

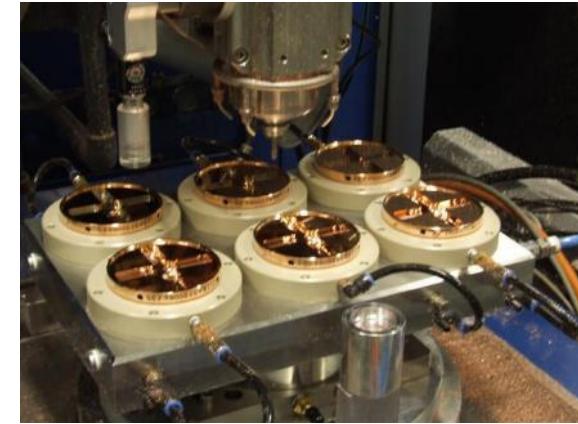
Micron-precision disk



Walter Wuensch, CERN



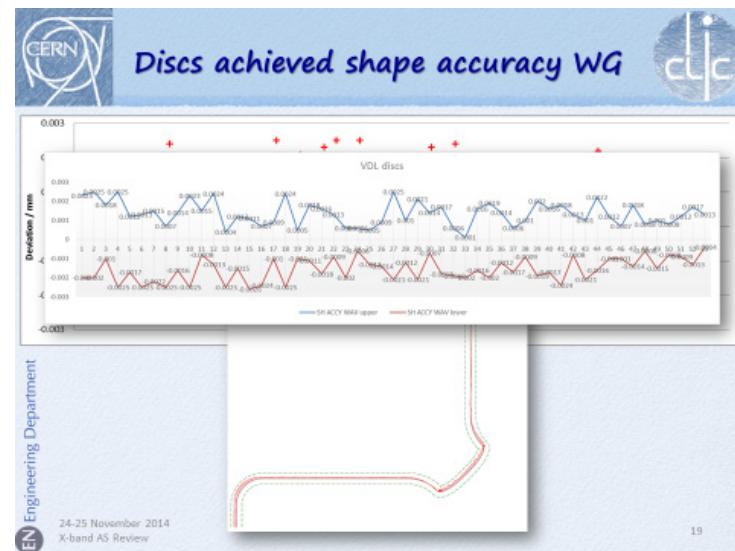
Commercial micron-precision machining



Micron-precision turning
and milling.

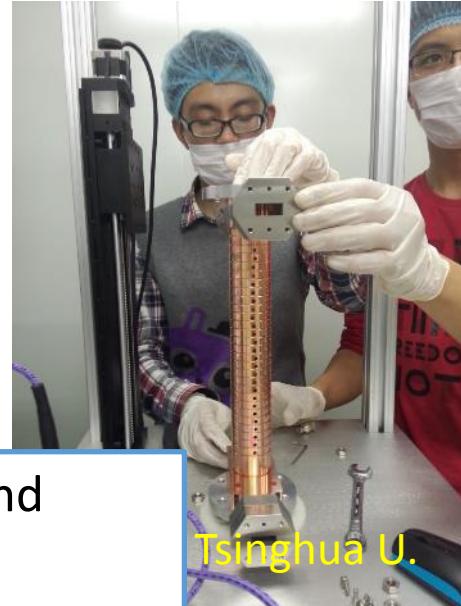
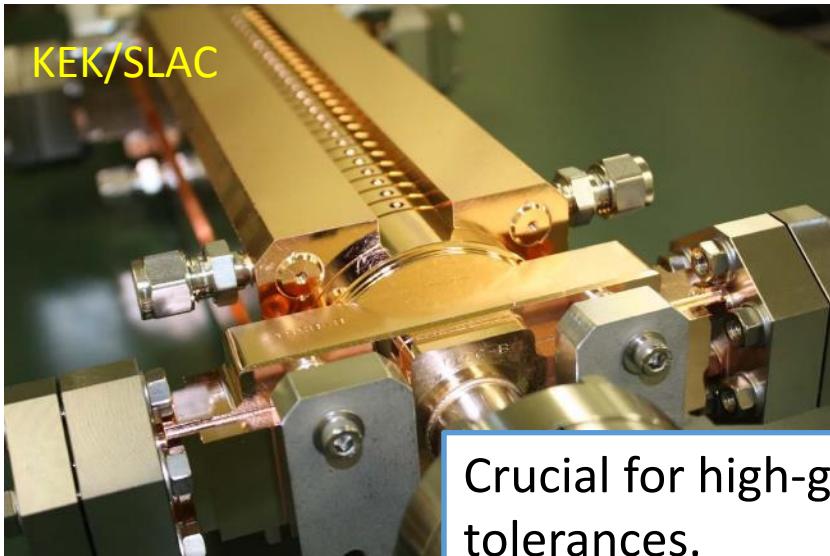
High-gradients, high-frequencies and tight mechanical tolerances go together.

We have a reasonable commercial supplier base capable of making the **micron tolerance** parts we need.





Heat treatment and joining



Crucial for high-gradient and tolerances.
Important cost driver.





Klystron based test stand

CLIC has a two-beam power source, demonstrated in CTF3. But to test enough structures we have used klystron based test stands:

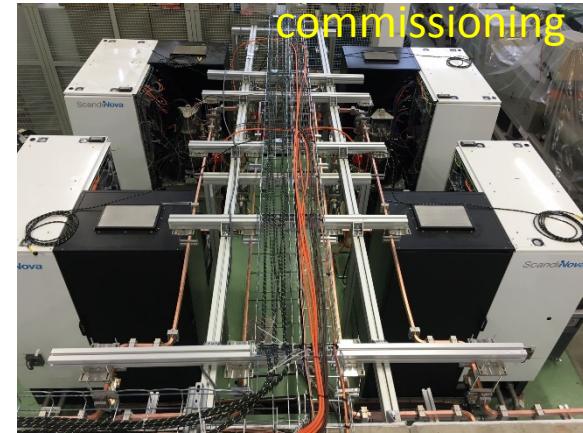
Please visit **TUPLR047**



XBox-1: 50 MW, 50 Hz

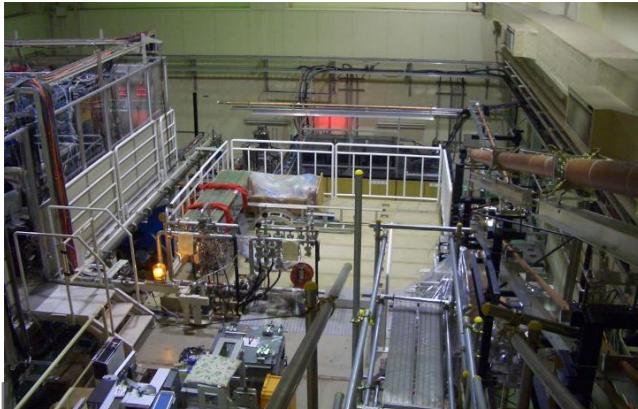


XBox-2: 50 MW, 50 Hz

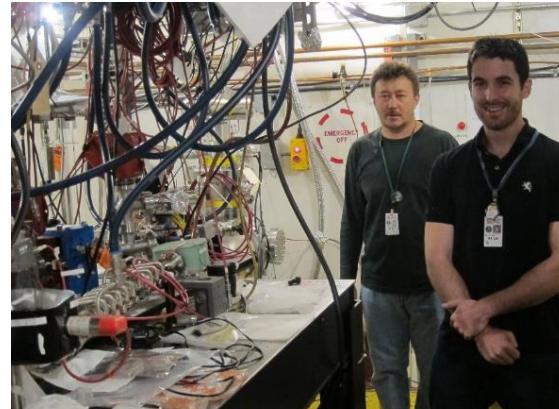


XBox-3: 50 MW, **400 Hz!**

NEXTEF
KEK



LINAC16,

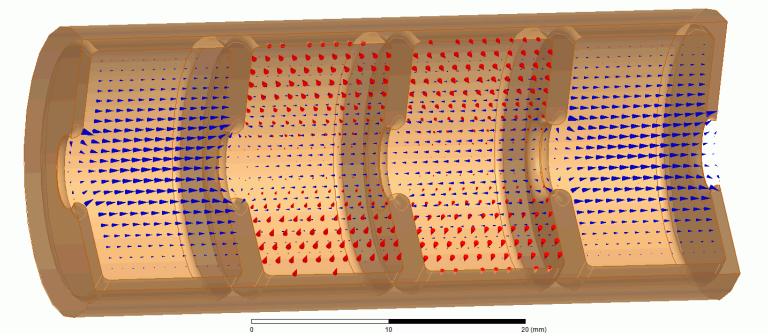


ASTA
SLAC

Ulrich Wuensch, CERN

Breakdown and rf design

BDR (BreakDown Rate) is the fraction of pulses which have a **vacuum arc**. Arc currents and lost acceleration result in lost luminosity on that pulse.



$$BDR \propto E^{30} \tau^5$$

BDR goes up with field level and pulse length.

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

CLIC specification:

3×10^{-7} 1/pulse/m

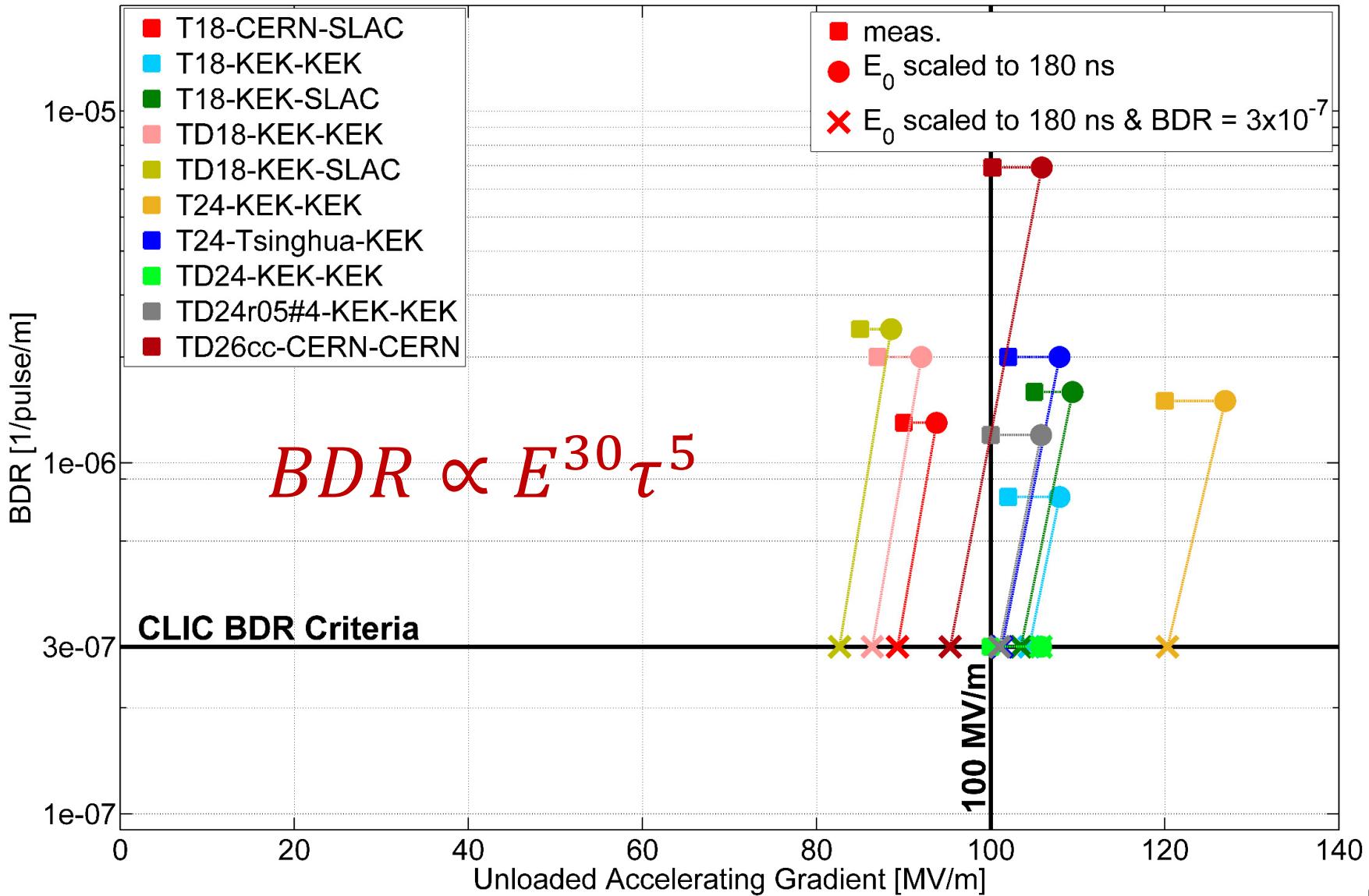
At 50 Hz, per structure:

1 BD every 3 days

Field for given BDR given by local power.
Allows **predictive design** of high-gradient performance and thus accelerator optimization.



Performance summary at CLIC specifications

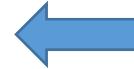




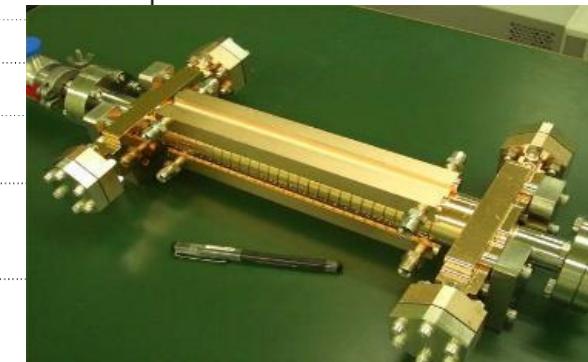
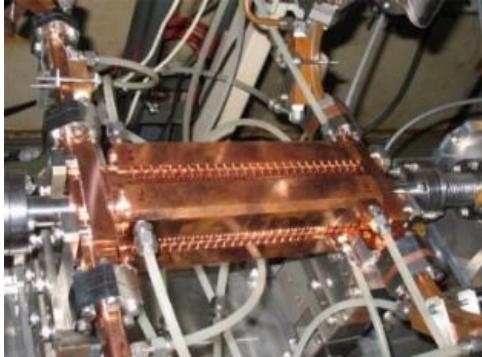
Gradient Perspectives



damped (mostly)



un-damped



100 MV/m

60

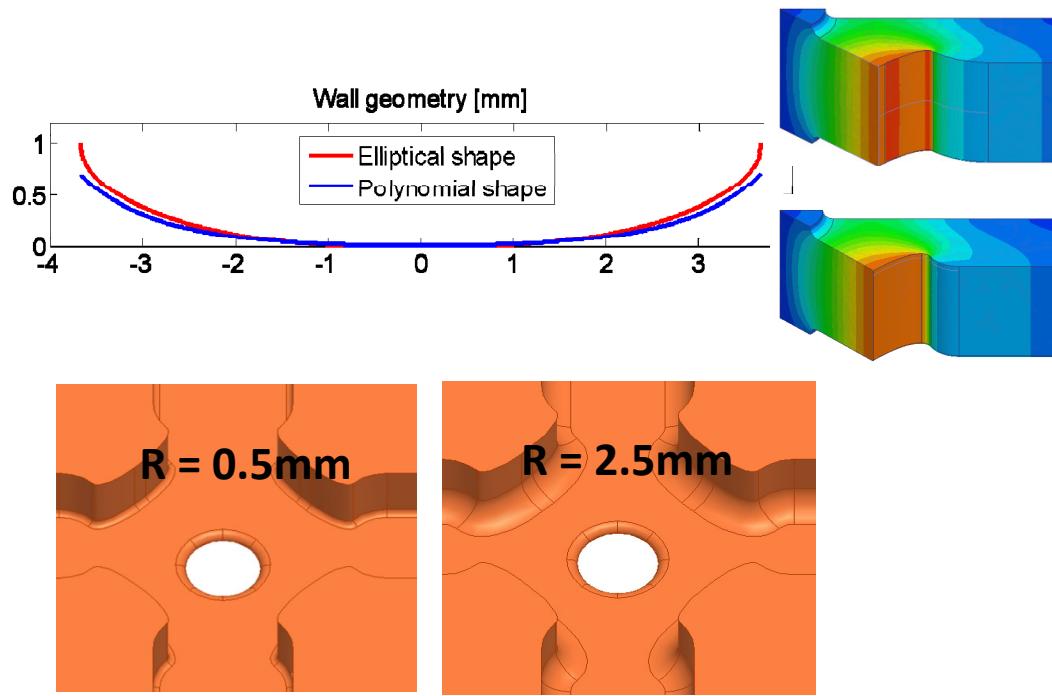
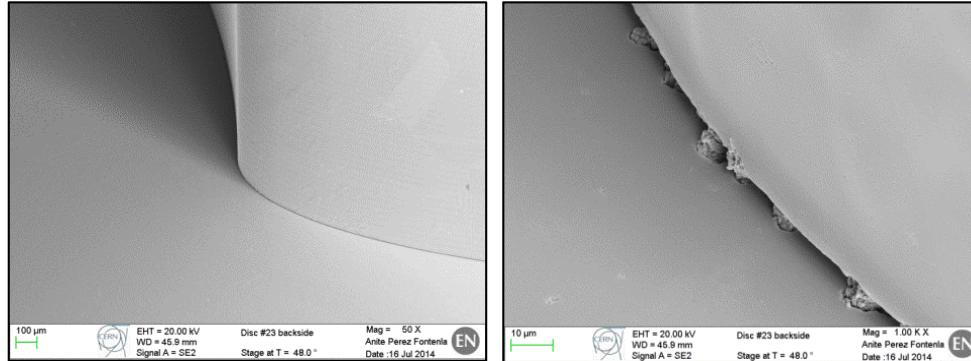
80

100

120

140

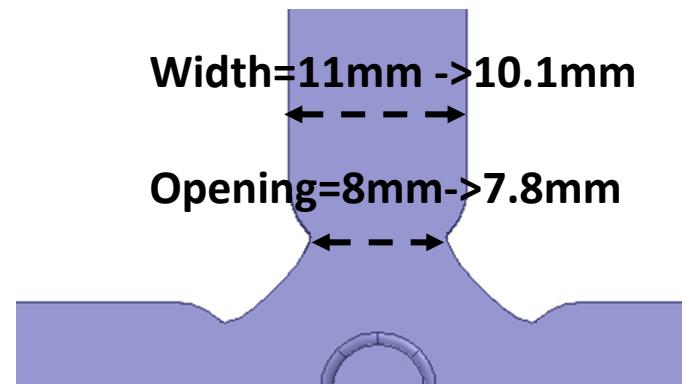
The next 20 MV/m



Analysing results and re-optimizing CLIC, we have a new baseline structure.

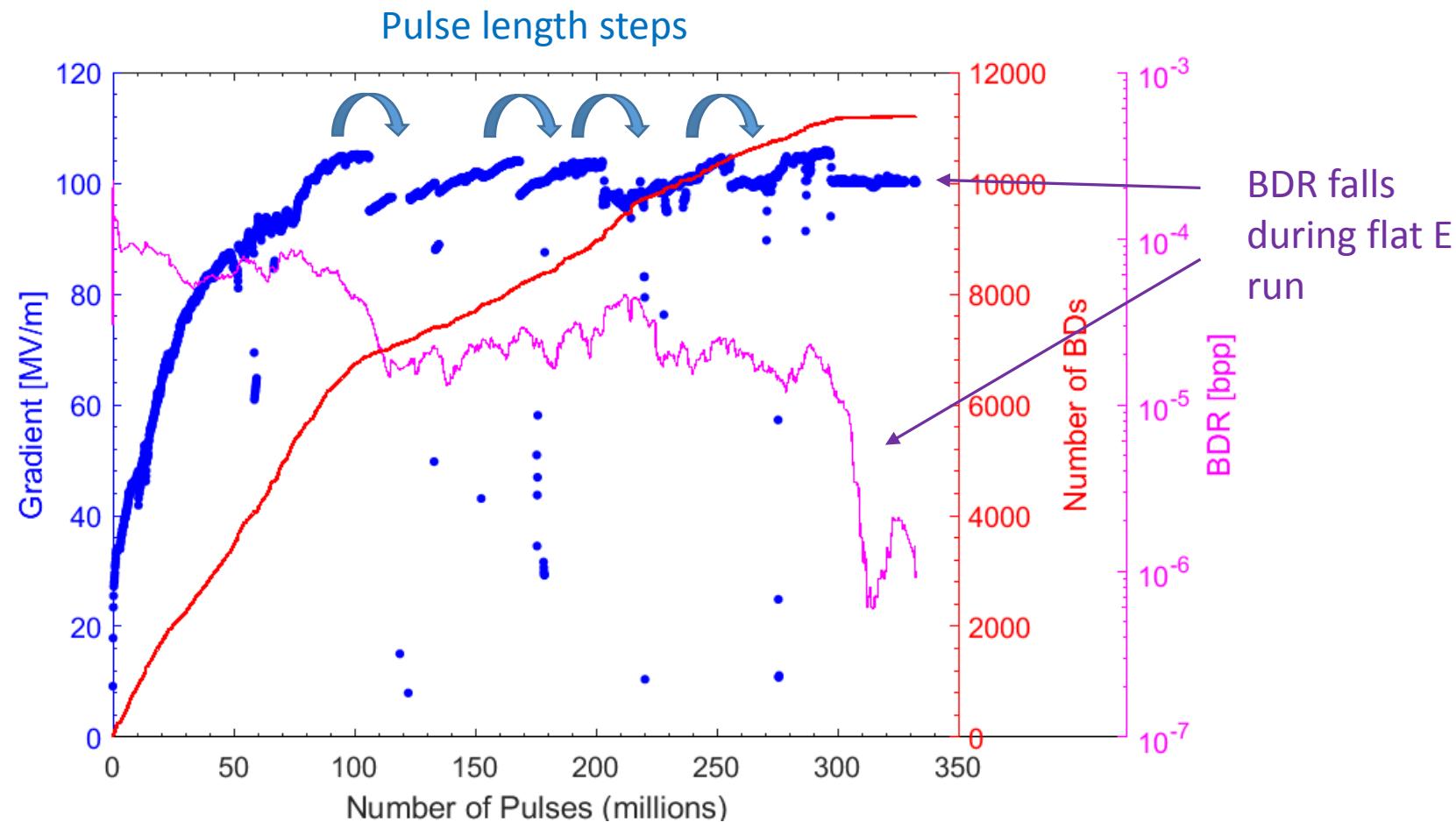
We expect to get to 120 MV/m unloaded, closing the gap we expect from beam loading.

Mechanical design done. To be built and tested.

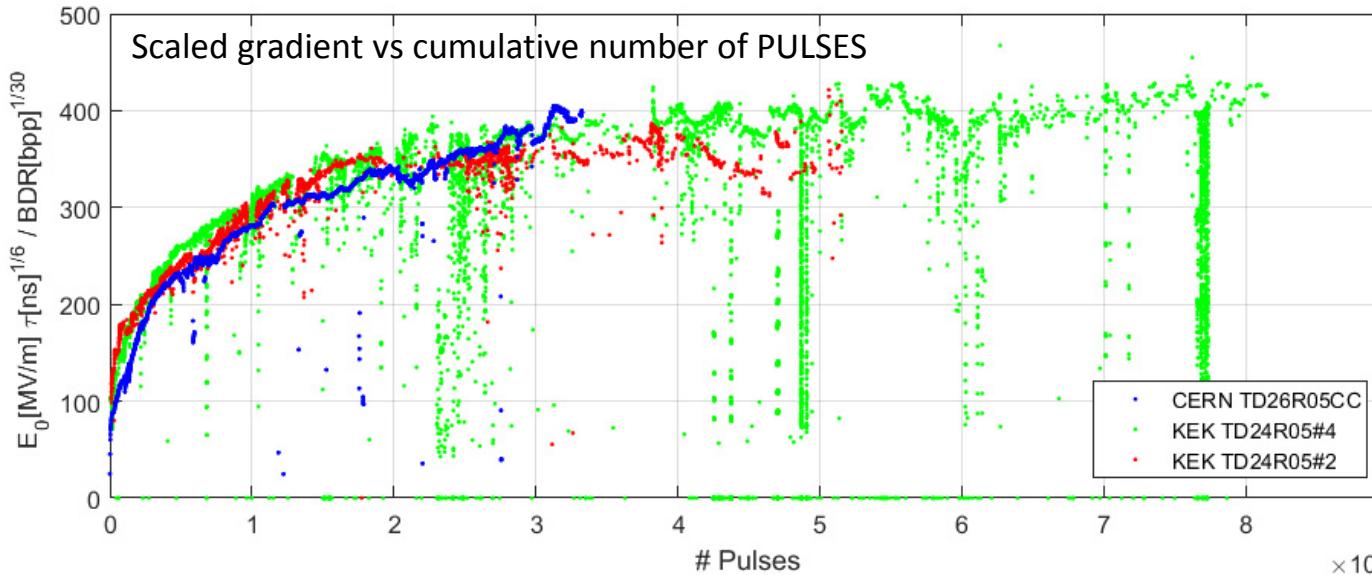


Conditioning

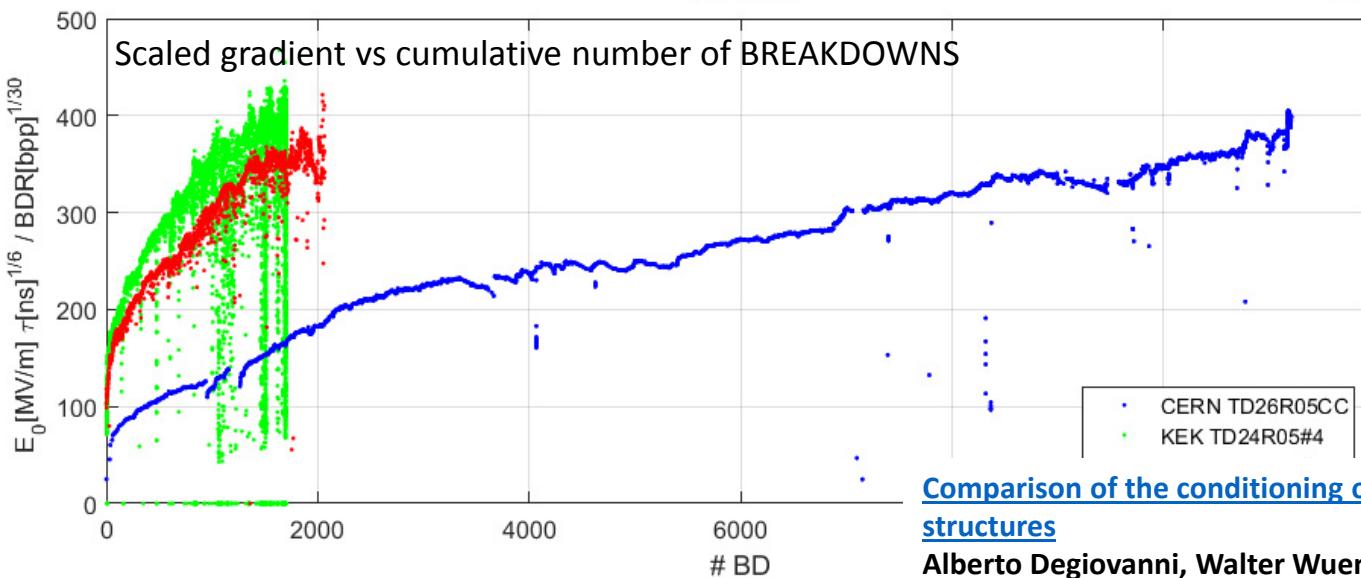
Accelerating structures do not run right away at full specification – pulse length and gradient need to be gradually increased while pulsing. Typical behaviour looks like this:



Comparing conditioning



Pulses



$BDR \propto E^{30} \tau^5$

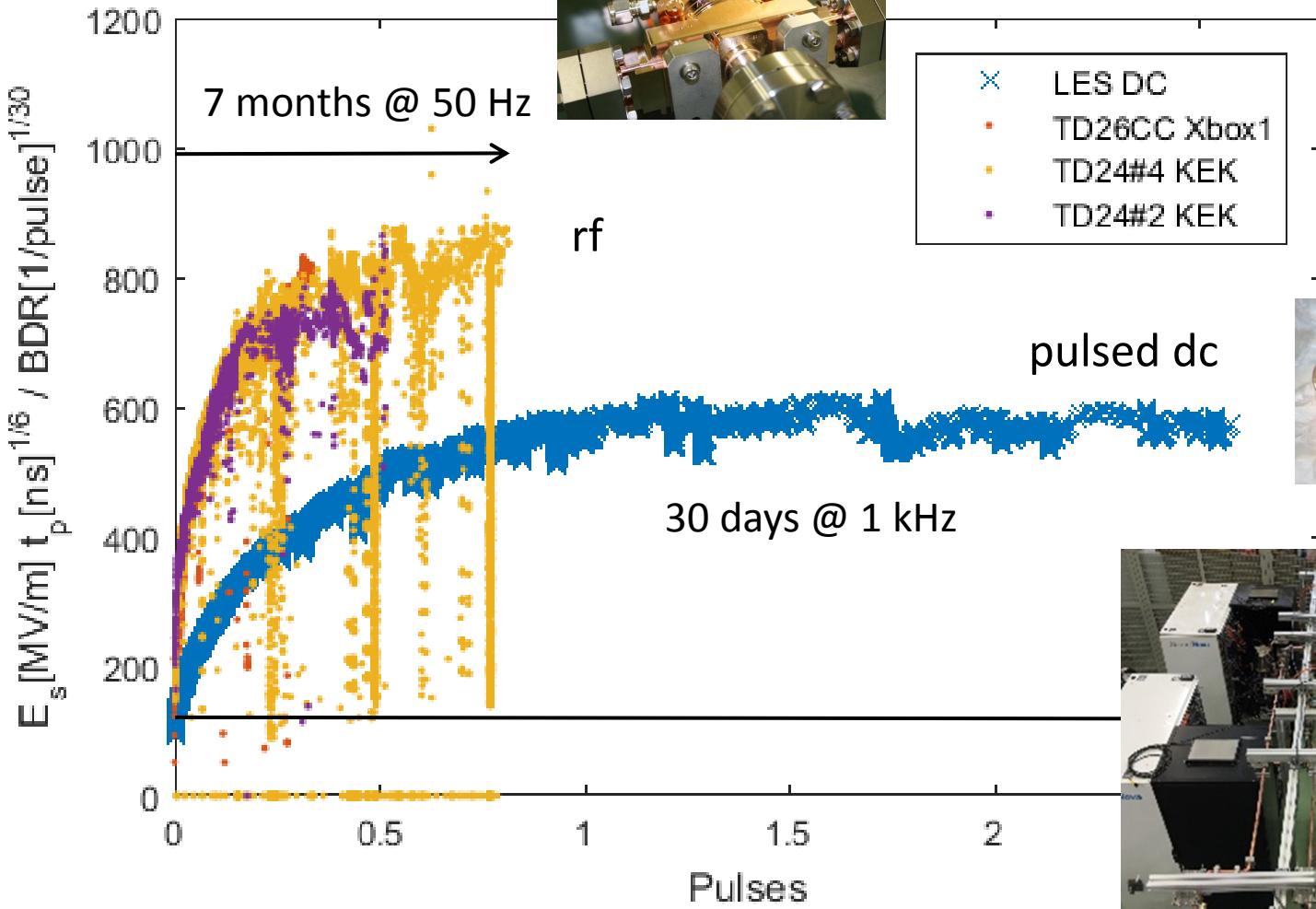
Breakdowns

Comparison of the conditioning of high gradient accelerating structures

Alberto Degiovanni, Walter Wuensch, and Jorge Giner Navarro
Phys. Rev. Accel. Beams 19, 032001 (2016) - Published 4 March 2016



Longer term operation



Longitudinal symmetry plane structures



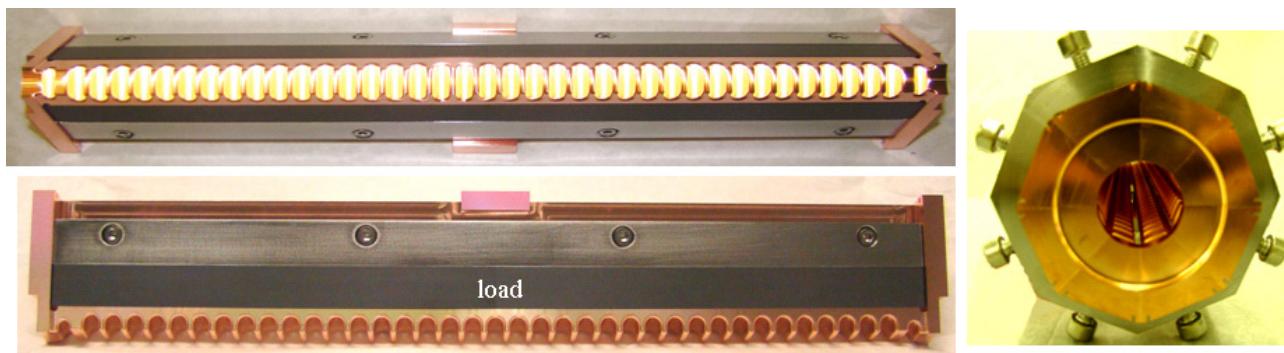
VS.



Potential advantages:

- Fewer parts, cheaper
- More assembly techniques possible
- Wider range of materials and material states possible

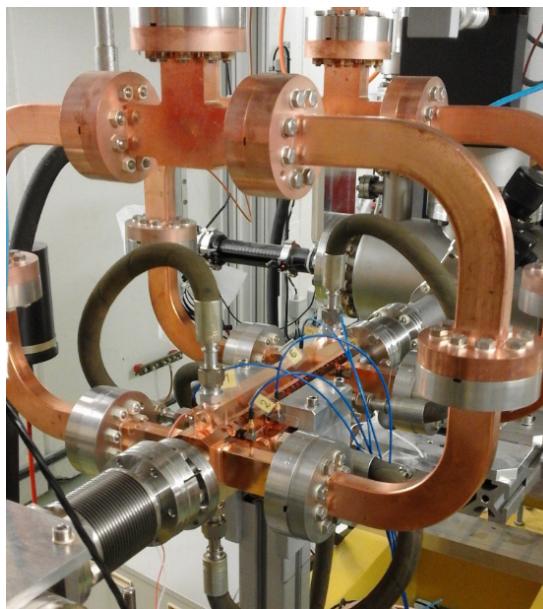
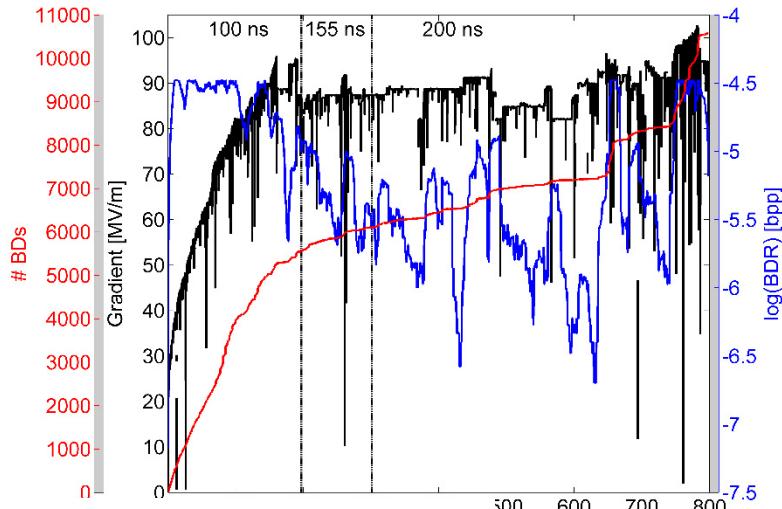
But can it hold the gradient?



CLIC two-beam power units, PETs, work very well in excess of 200 MW!

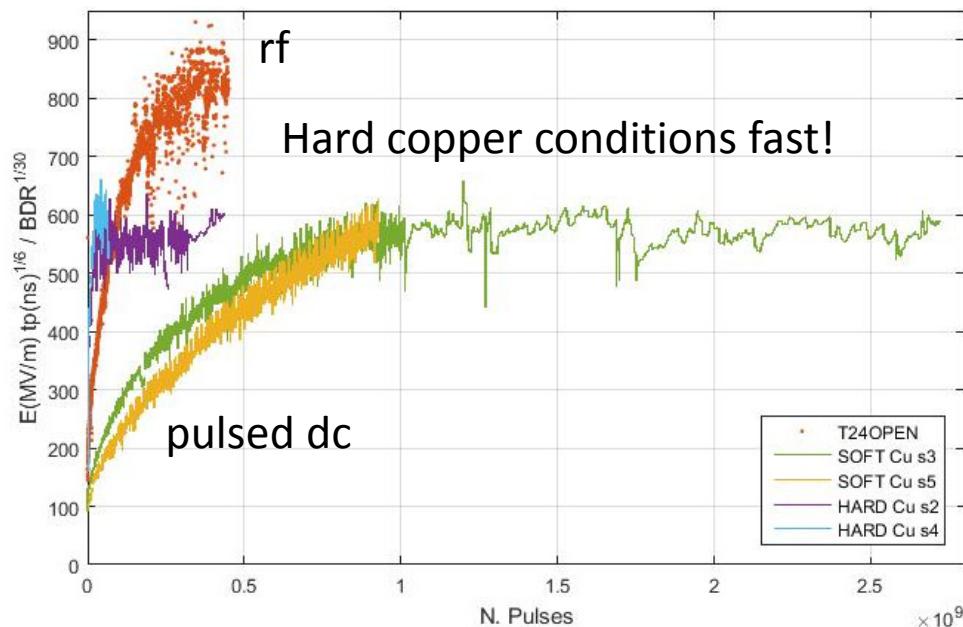
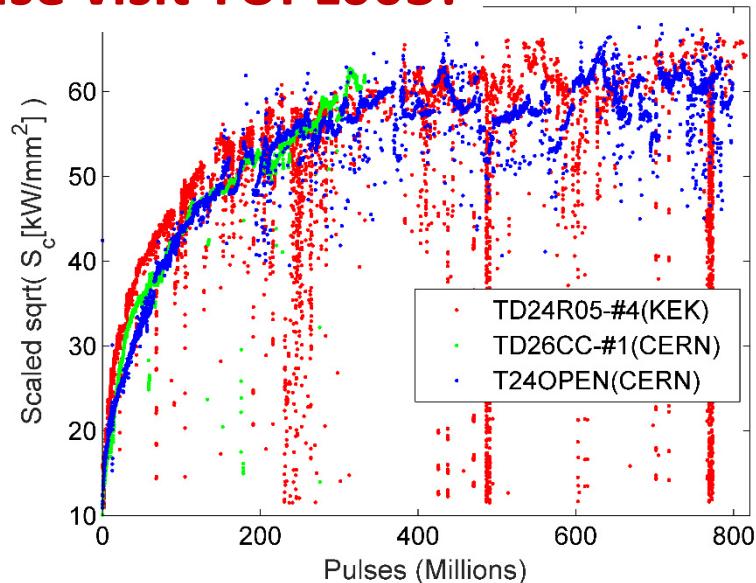


Structure in halves: High-power test



Installed in XBox-2
Designed and tested by CERN, built at SLAC.

Please visit **TUPL003!**





Part II: Applications of high-gradient



General considerations



High gradient is clear when high beam energy is desired and site length is fixed, like a 3 TeV linear collider.

Also high gradient reduces the costs which scale with length.

On the other hand it raises peak power which is another important cost driver:

$$P' \propto G^2 \quad \text{so} \quad P \propto G$$

Optimization is complex.

For example the optimum gradient is 70 MV/m for the 380 GeV initial energy stage of CLIC.

And there seem to be a number of applications which have a gradient in the 60-100 MV/m.

There is an additional benefit from X-band – average power. Shunt impedance is high and pulse length is short so repetition rate can be high.

XBox-3 will run at 400 Hz, and 1 KHz is within reach.



Practical considerations



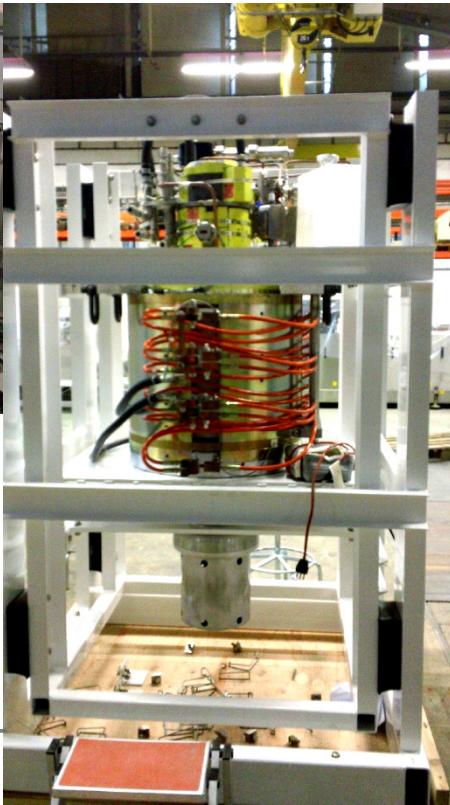
The CERN XBoxes are all based on **commercial solid state modulators and commercial klystrons**.

Pulse compressors and high-power WG system have mostly been made in hybrid commercial with lab based assembly.

So high-gradient X-band is ready for your application!

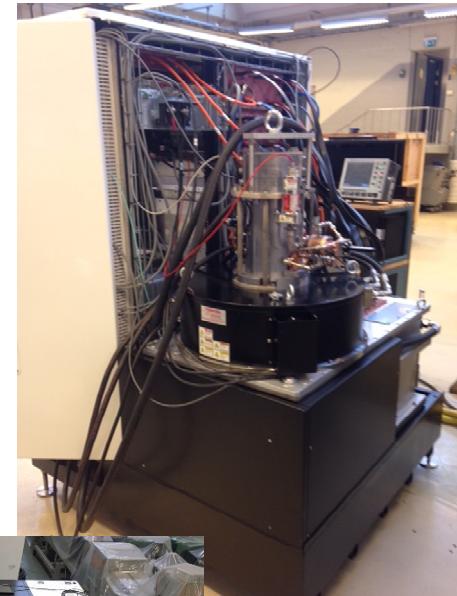
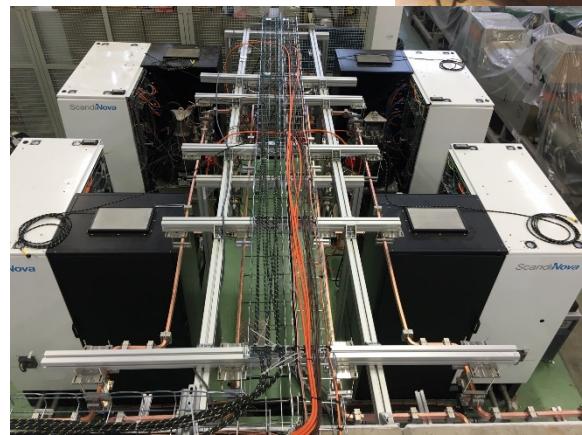


XBox-2
ScandiNova
CPI



LINAC16, East Lansing, 2016

XBox-3
ScandiNova
Toshiba



Hensch, CERN

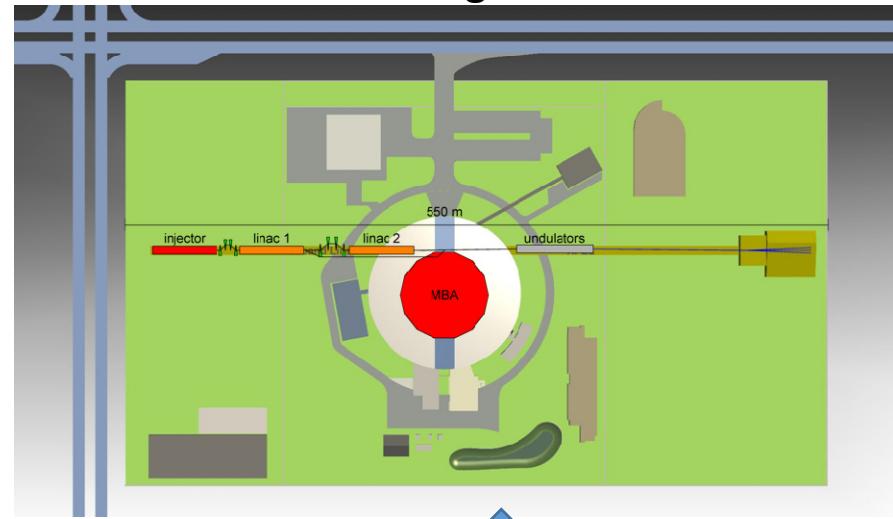
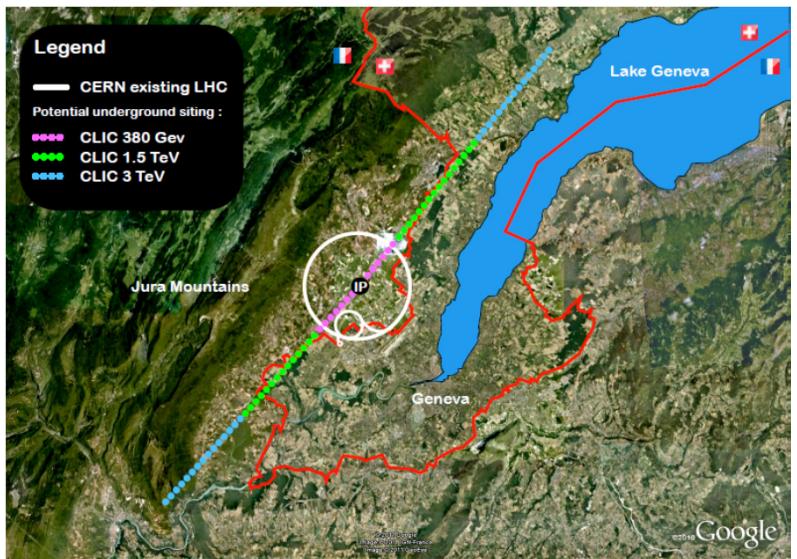


CLIC

Applications of X-band acceleration

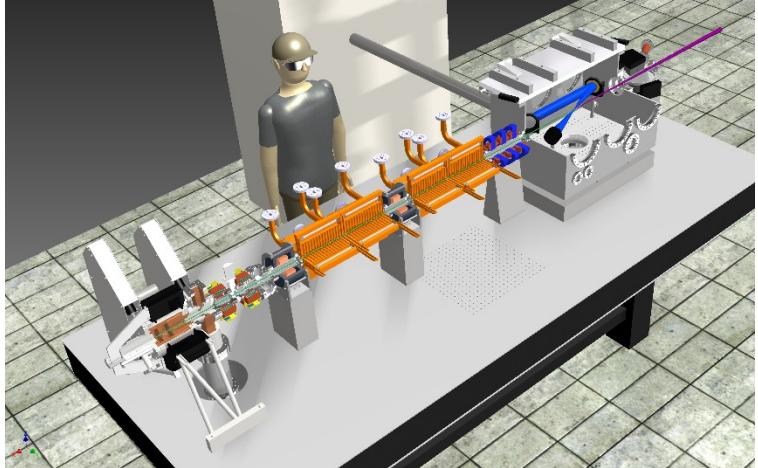


Australian Light Source

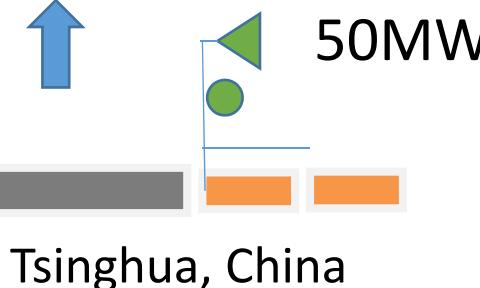


Linear collider - TeV

XFEL – 1 to 10 GeV



Thompson/Compton
source – few 100s MeV



Smart*Light, NL
LINAC16, East Lns
Compact Compton source
few 10s MeV

Tsinghua, China

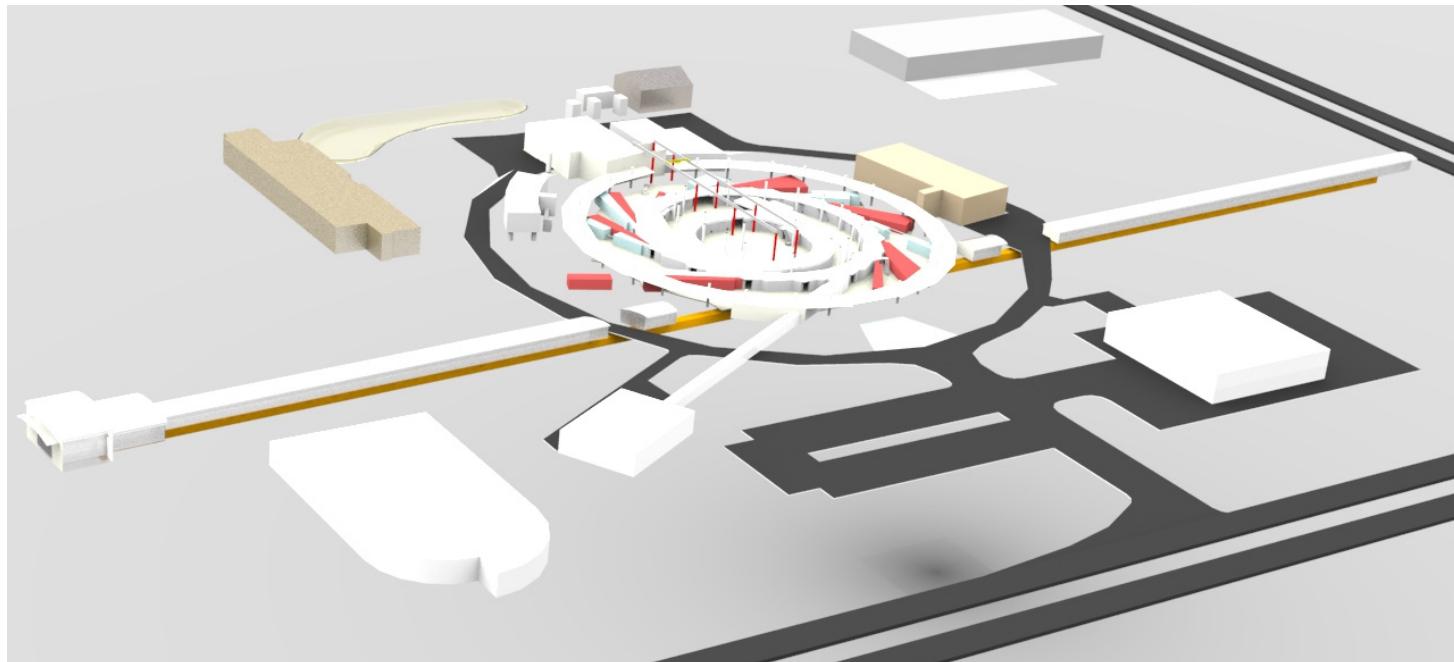
AXXS

AXXS – Australian X-band X-ray Source

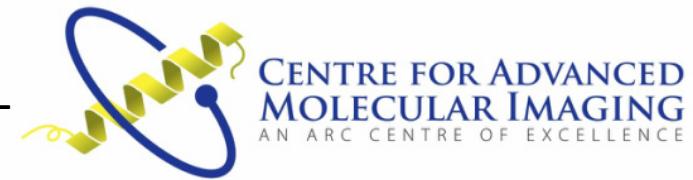
AXXS n. /'æksɪs/ *fig.* A central prop, which sustains any system.

Development plan for the Australian Light Source community:

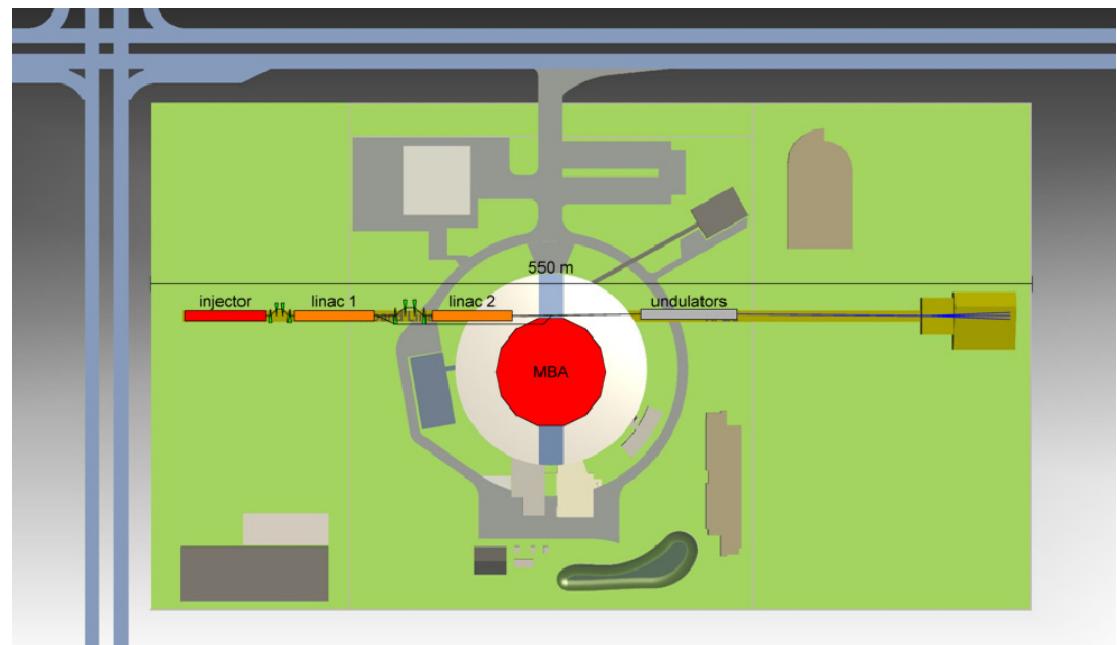
1. develop the remaining beamlines (space for an additional 6 IDs)
2. upgrade the storage ring lattice to MBA (compact MAX IV magnets)
3. upgrade the injector to a full energy x-band linac (3 GeV)
4. upgrade to additional linac for XFEL (6 GeV)



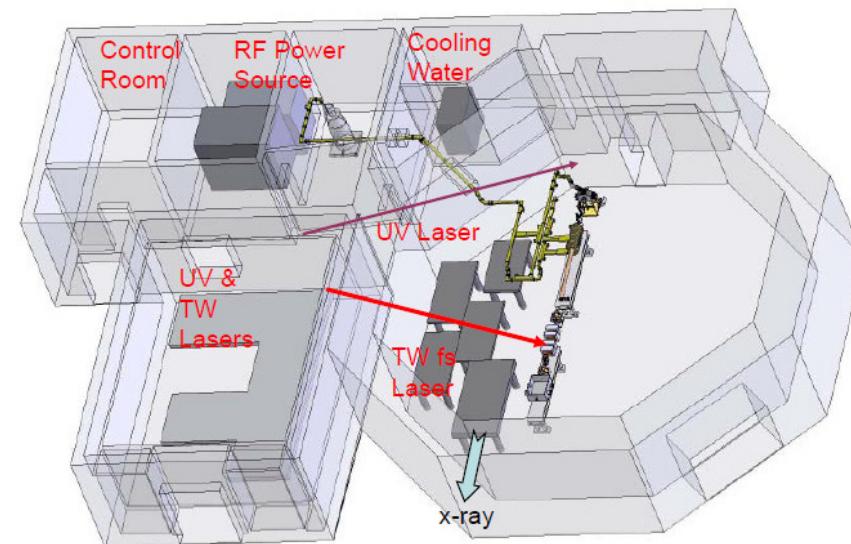
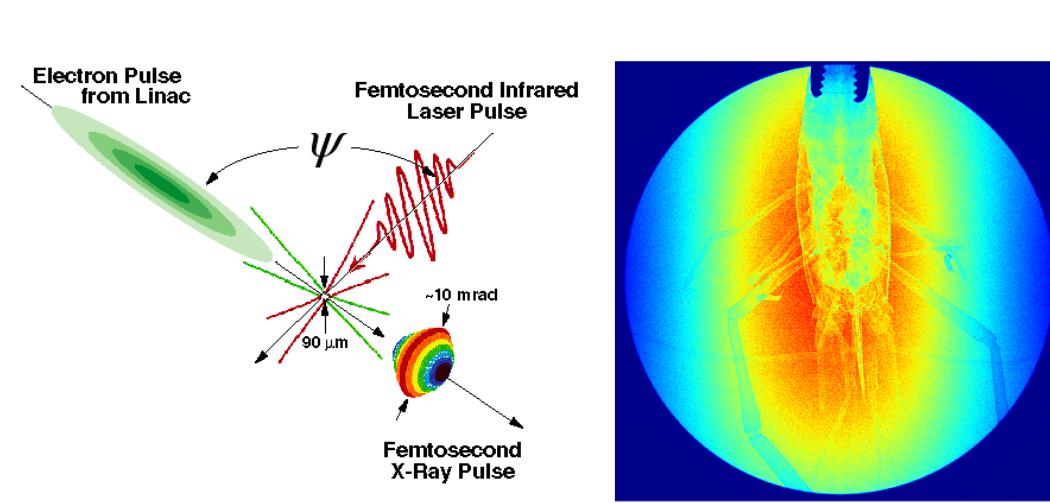
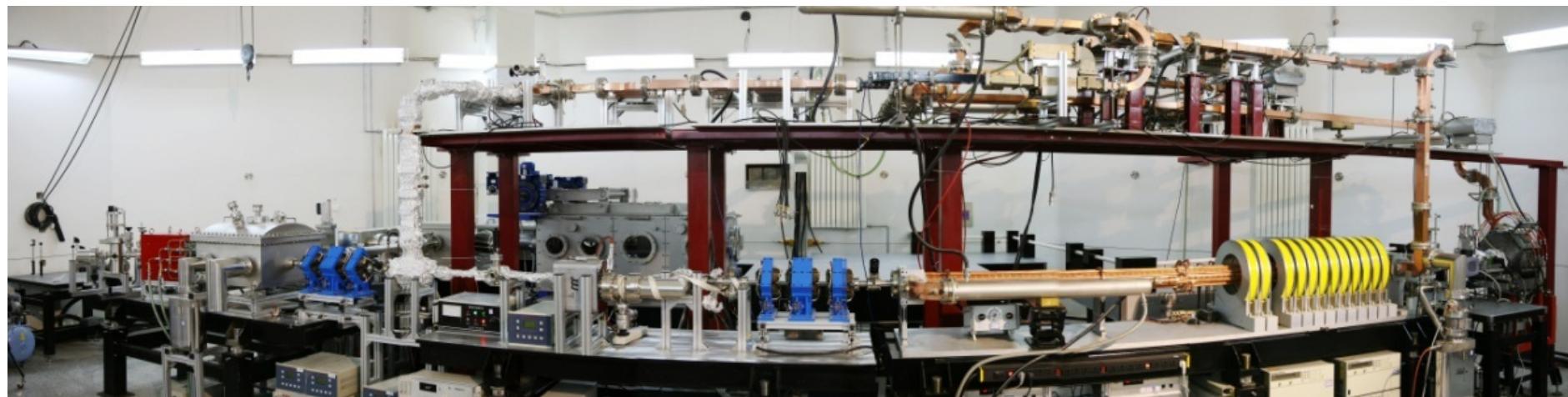
- Strong XFEL user base with regular beamtime on LCLS and members of review committees for European XFEL
- Strong government funding, especially in life sciences



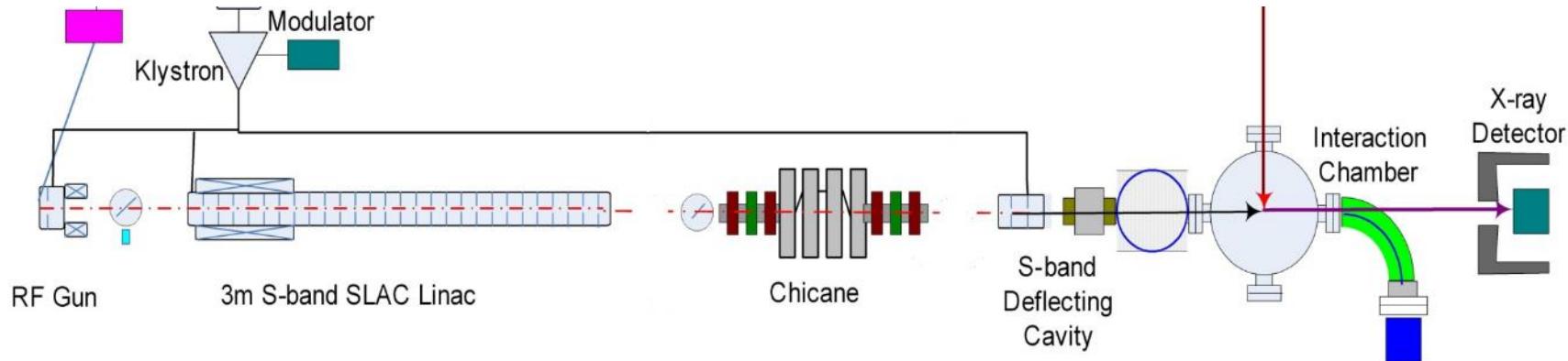
- Site constraint 550 m:
- Same tunnel, energy and source points for storage ring upgrade.
- Time constraints: need to finish building out the remaining beamlines before justifying a new ring or FEL.



Tsinghua Thomson-Scattering X-ray Source (TTX)



TTX linac upgrade proposal



1 year



$1.5\text{m} \times 30\text{MV/m}$

2~4 years



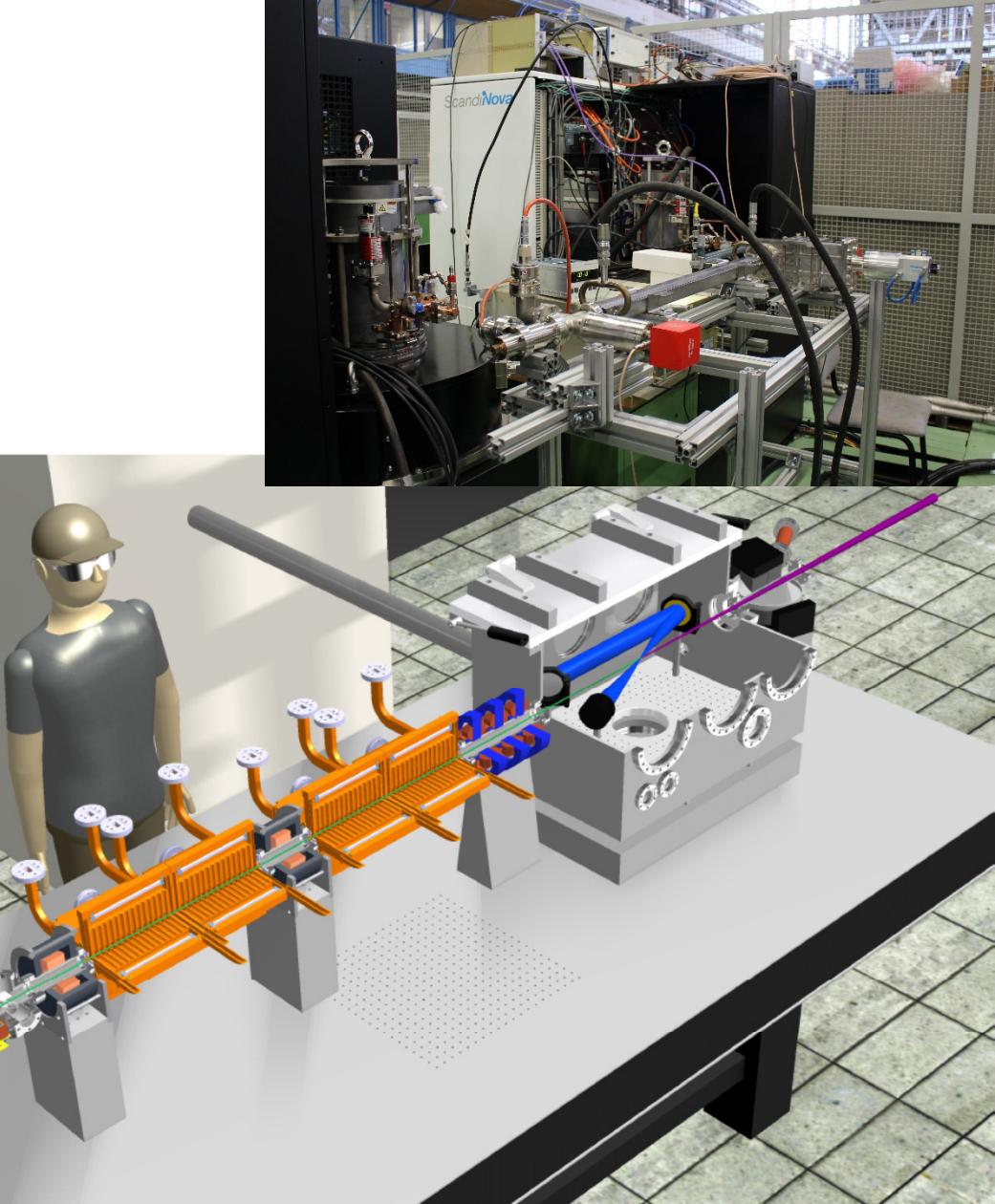
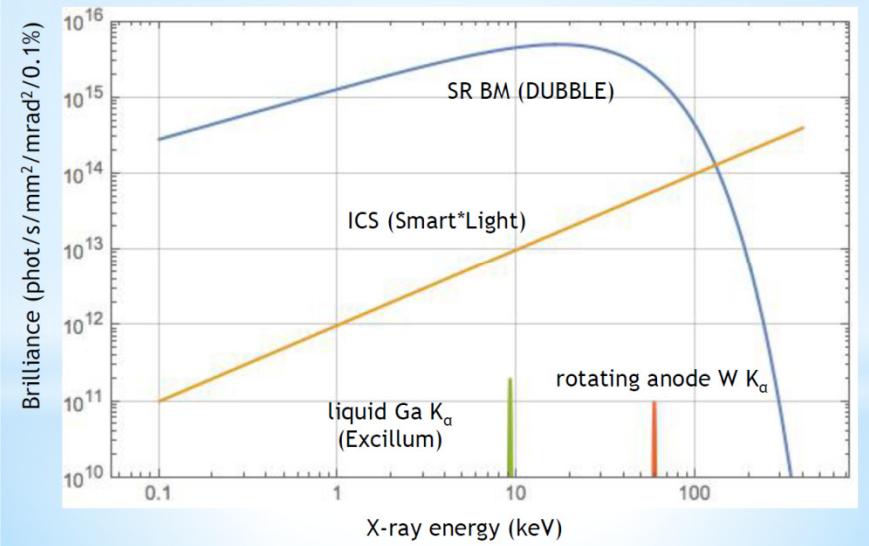
50MW

$1.5\text{m} \times 30\text{MV/m} + 2 \times 0.6\text{m} \times 75\text{MV/m}$

Replace 3-meter with 1.5-meter x 30MV/m

Add X-band to the energy ~150MeV

X-ray photon flux and brilliance

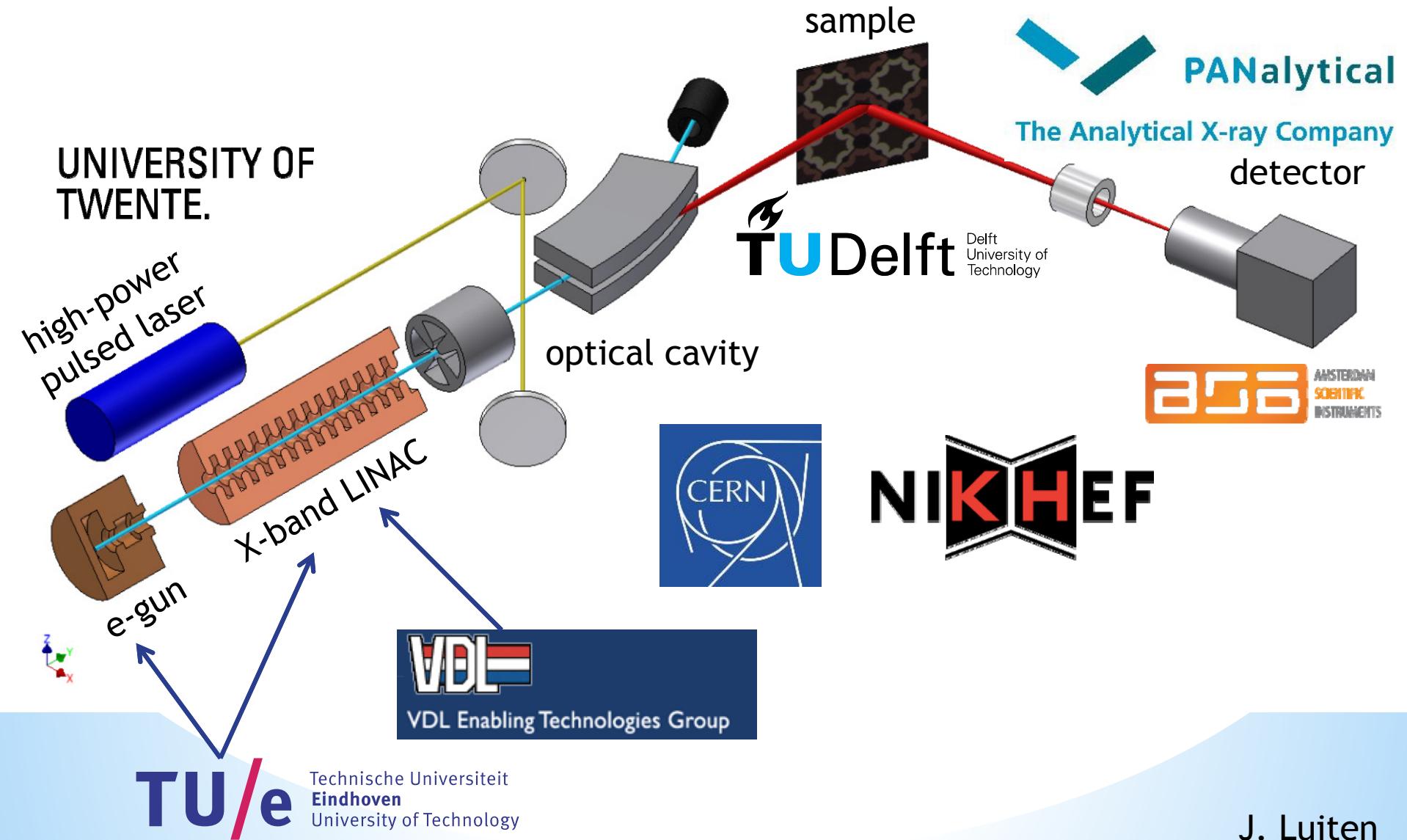


J. Luiten

Smart*Light:

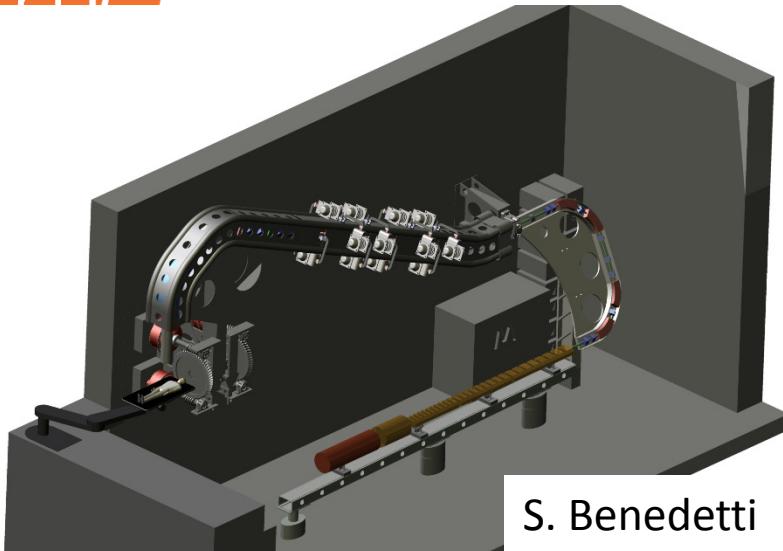
A table-top alternative for synchrotron light sources

Compton Back Scattering source



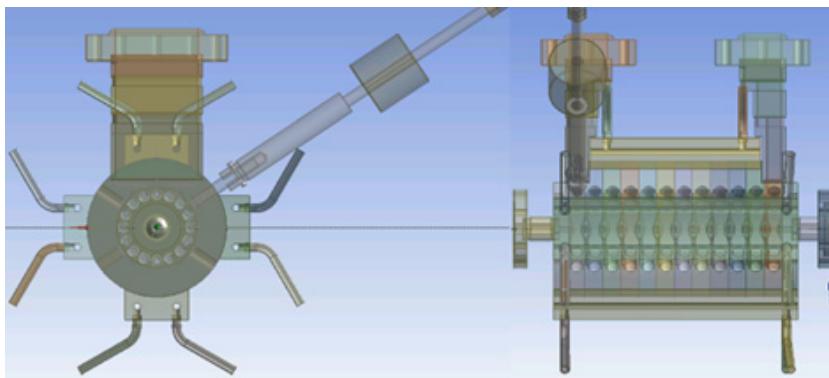


High-gradient for proton therapy



S. Benedetti

Potential application: TULIP developed by
TERA foundation

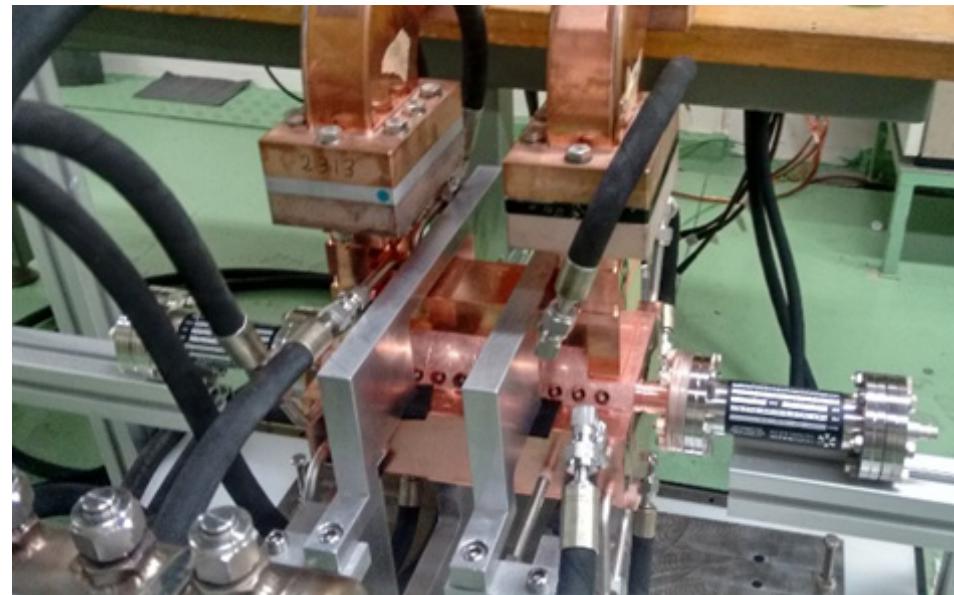
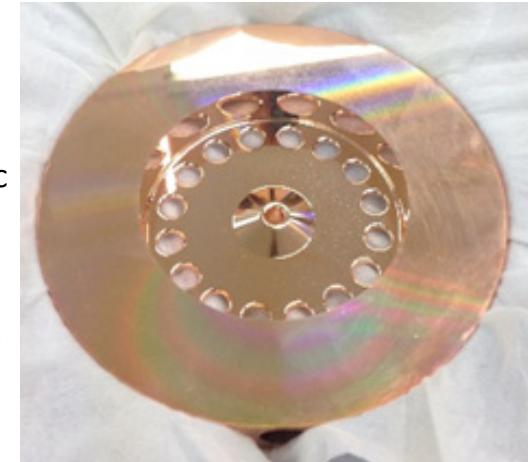


Test structure funded by CERN Knowledge
Transfer department.

LINAC16, East Lansing, 27 September 2016

3 GHz backward
travelling wave.
50 MV/m based on S_c

Installed in CTF3,
ready for high-power
test to start.



Please visit **MOPLR048**



Probe

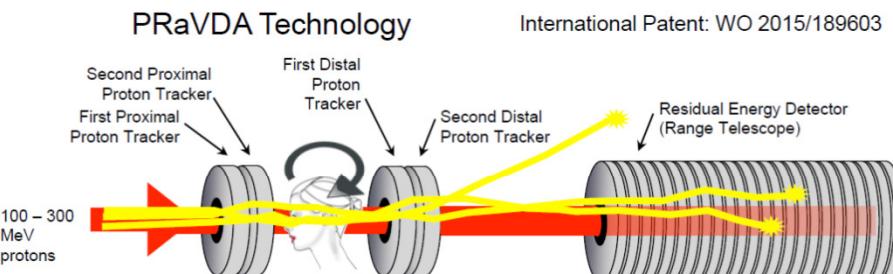


MANCHESTER
1824 Lancaster University



PROBE: PROTON BOOSTING EXTENSION FOR IMAGING AND THERAPY

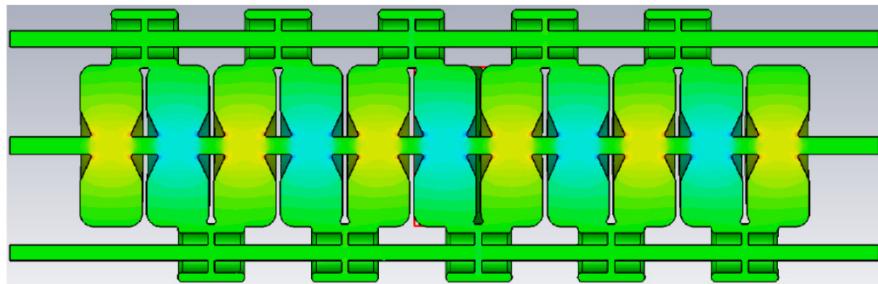
Sam Pitman
Dr Graeme Burt
Dr Hywel Owen
Dr Robert Apsimon



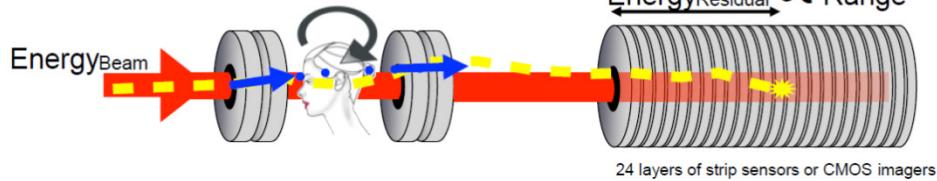
3GHz Side Coupled Standing Wave Structure

- ❖ Travelling wave <52MV/m
- ❖ Side coupled 54MV/m
- ❖ Higher Power (50MW)
- ❖ Aggressive gradient limits
 - ❖ Epeak < 200MV/m

❖ Thin septum (2mm)



$$\text{Energy}_{\text{Absorbed}} = \text{Energy}_{\text{Beam}} - \text{Energy}_{\text{Residual}}$$



S. Pitman



ARIES

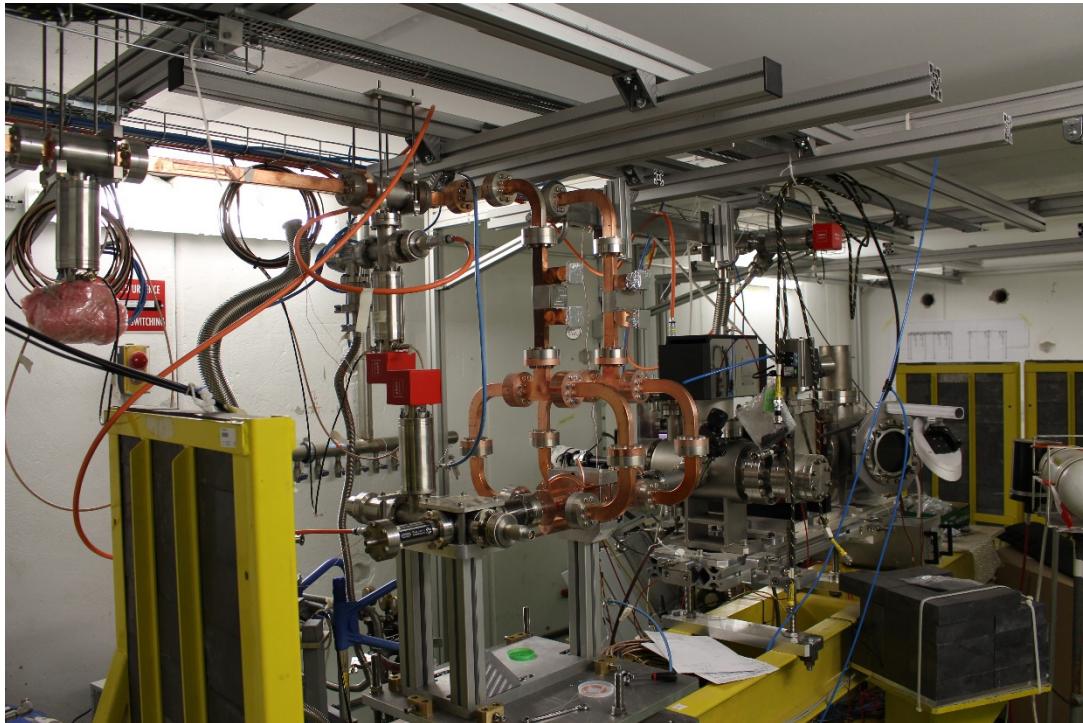


The XBoxes are a **TNA** (Trans National Access) in the ARIES H2020 program.

Support to researchers from other laboratories for experiments carried out in the XBoxes.

May 2017 to April 2021.

ARIES – Accelerator research for European Science and Society



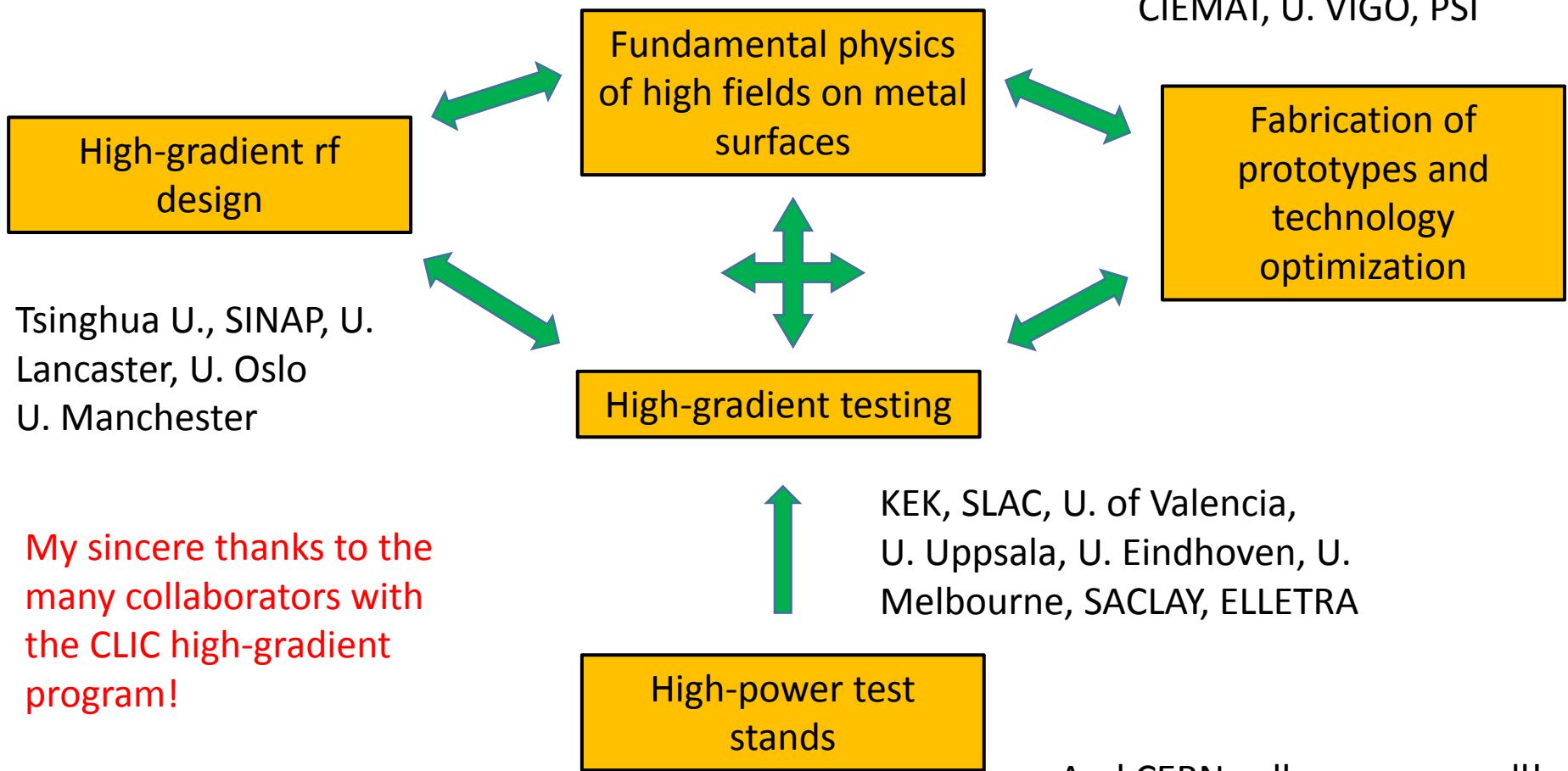
Your structure or diagnostic here!



Acknowledgements



U. Helsinki, Hebrew U. of Jerusalem,
U. Tartu, Technical U. Lisbon, IAP Sumy



My sincere thanks to the many collaborators with the CLIC high-gradient program!

LINAC16, East Lansing

Thank you!

And CERN colleagues as well!

Walter Wuensch, CERN