High-Gradient Normal Conducting Accelerator Development

MeVArc 2012

Walter Wuensch, CERN

2 October 2012

Introduction

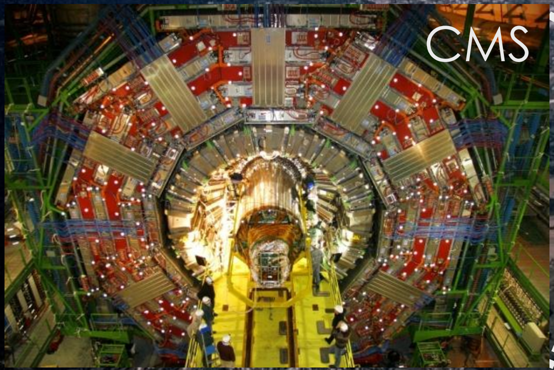
For nearly 25 years the high-energy physics community has been developing the technology needed to build a TeV-range electron positron linear collider.

One of the options which has been pursued is CLIC, which seeks to push normal conducting acceleration up to 100 MV/m – which has lead to a significant effort to try understand VACUUM ARCS quantitatively and in detail. Such understanding would us to optimize the design of the machine even more precisely with the potential for huge cost savings.

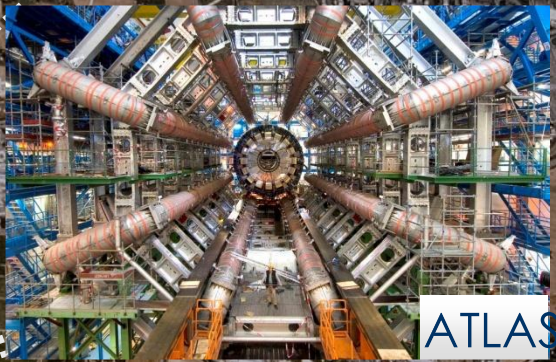
I would like to cover some important recent developments and directions for the CLIC study:

- The impact of LHC results on the motivation for a linear collider and project planning for CLIC.
- Some recent progress in achieving the accelerating gradient and summarize the big open questions.
- Introduce new efforts to apply our high-gradient technology, and through that our study of vacuum arcs, to other projects.

Today:
a New Era in Fundamental Science

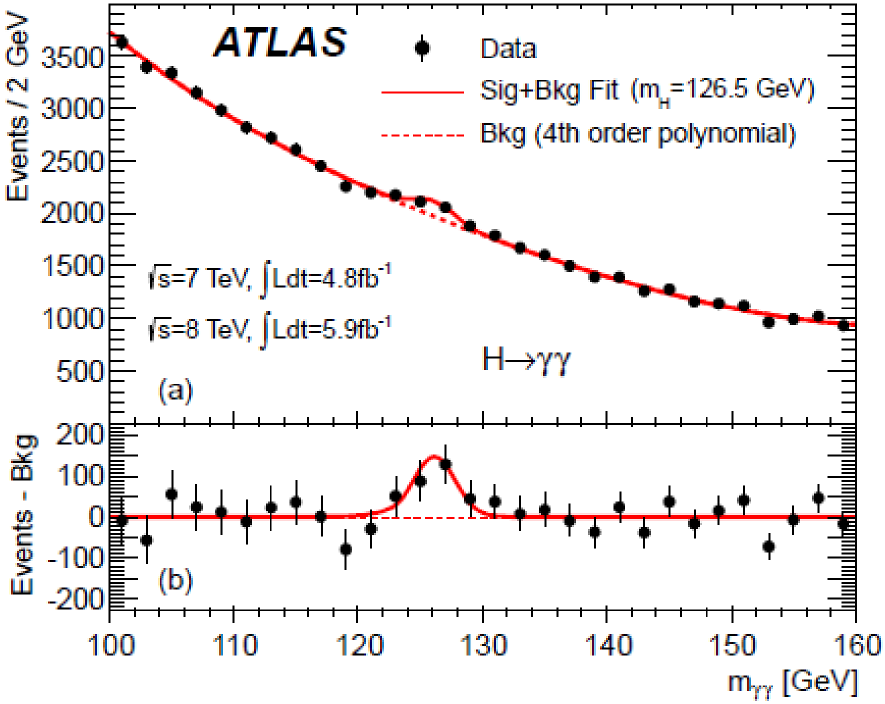


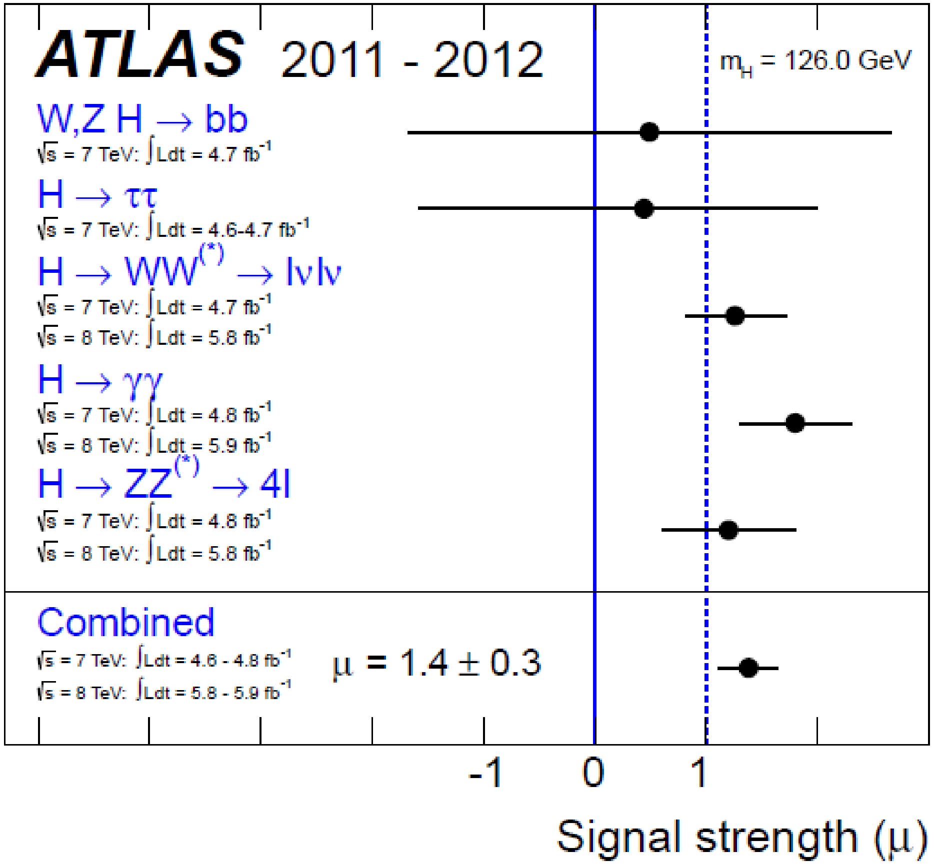
Exploration of a new energy frontier
Proton-proton and Heavy Ion collisions
at E_{CM} up to 14 TeV (in 2010/11: 7 TeV)



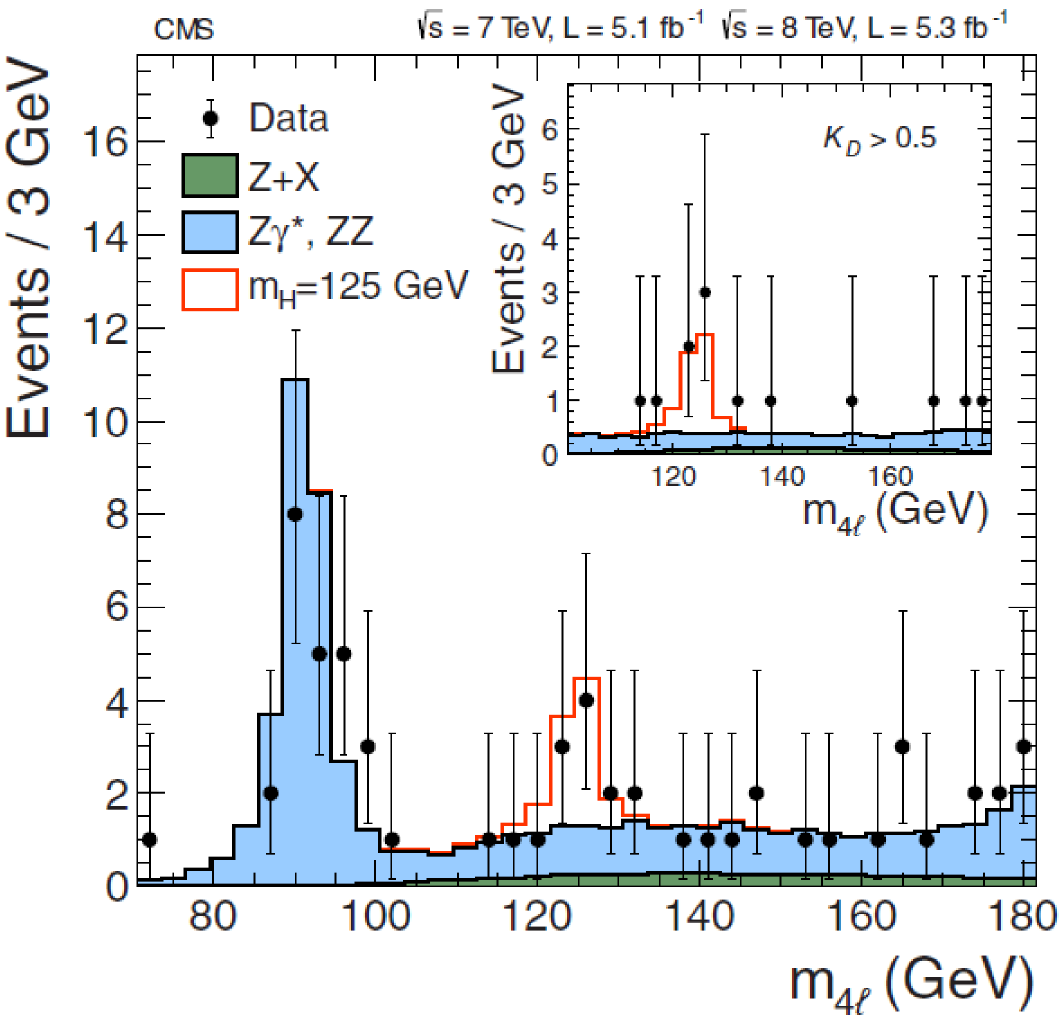
Published Observations of a "Higgs-like Boson" by ATLAS (a selection)

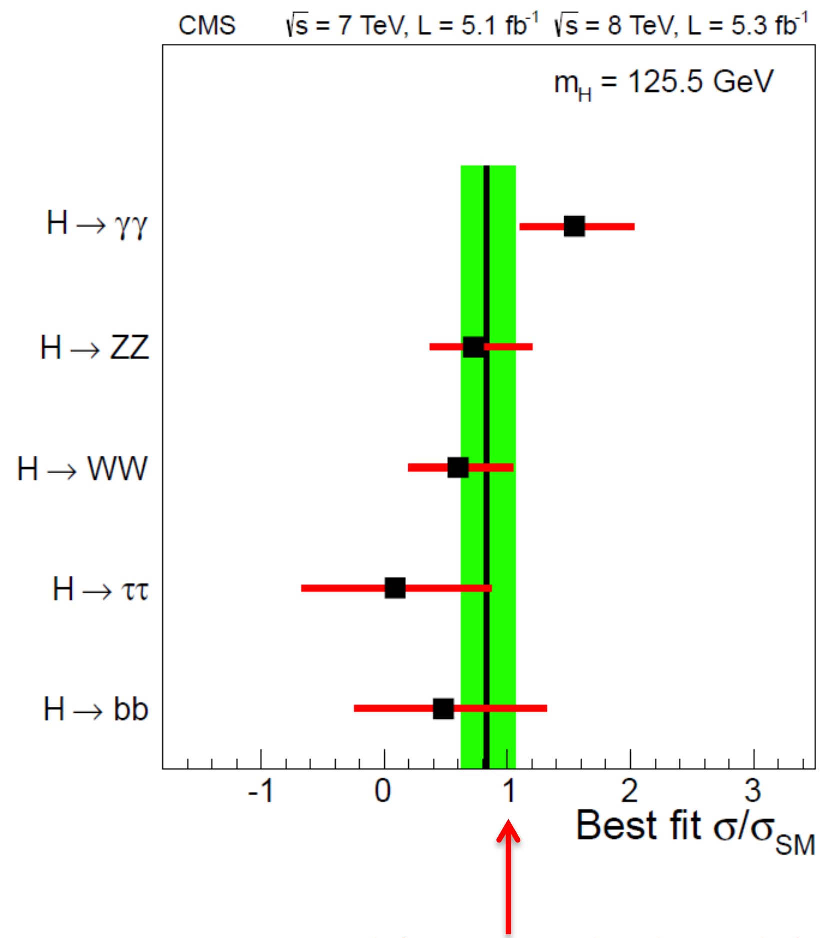
Expected for a standard-model Higgs of mass 126 GeV





Published Observations of a "Higgs-like Boson" by CMS (a selection)

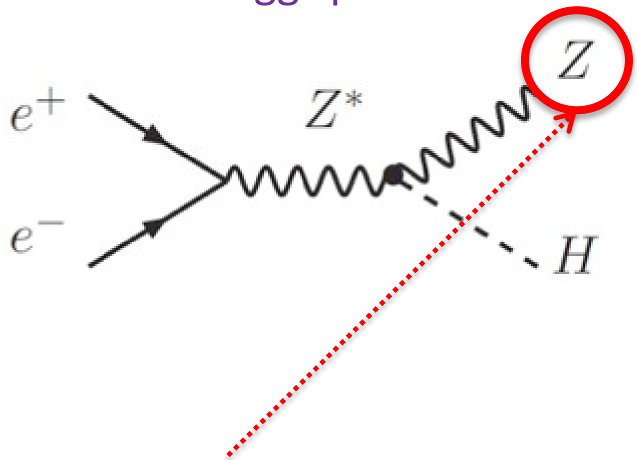




Expected for a standard-model Higgs of mass 125.5 GeV

Example: Higgs coupling to Z (and Higgs mass meas.)

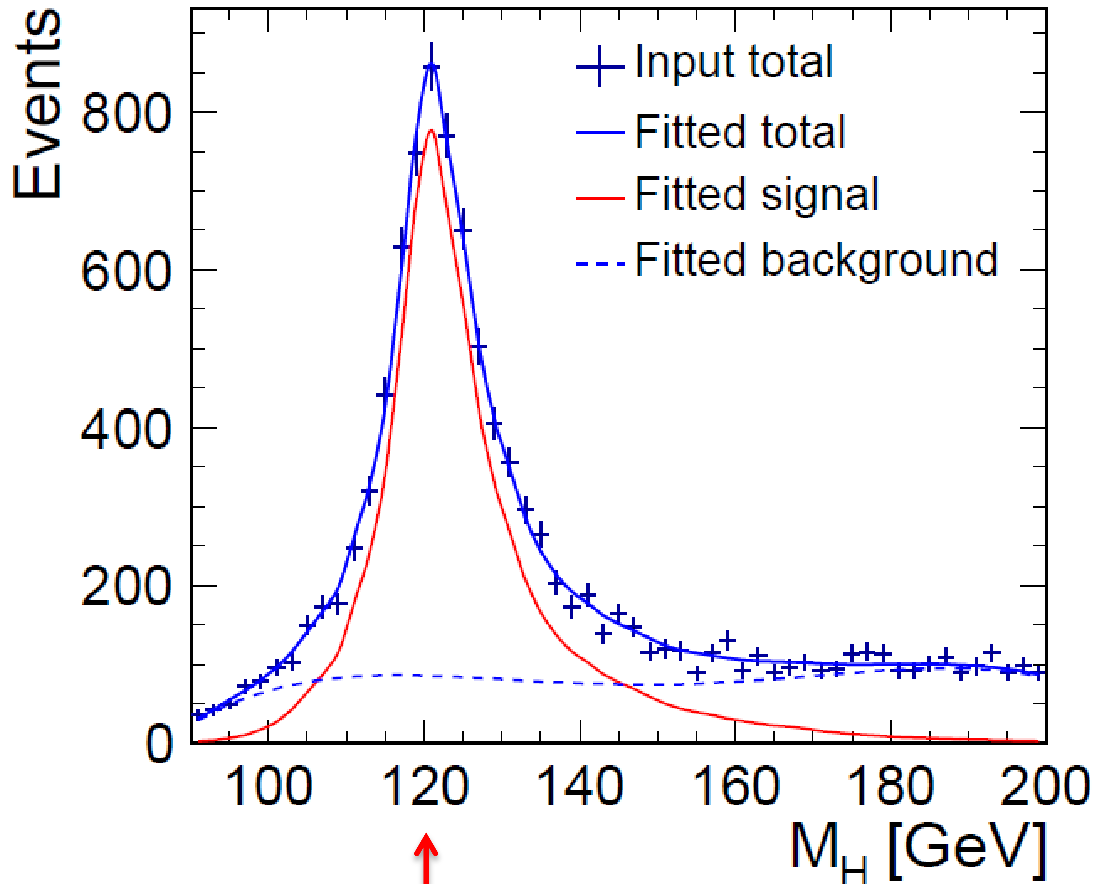
dominant Higgs production mode at lower energies:



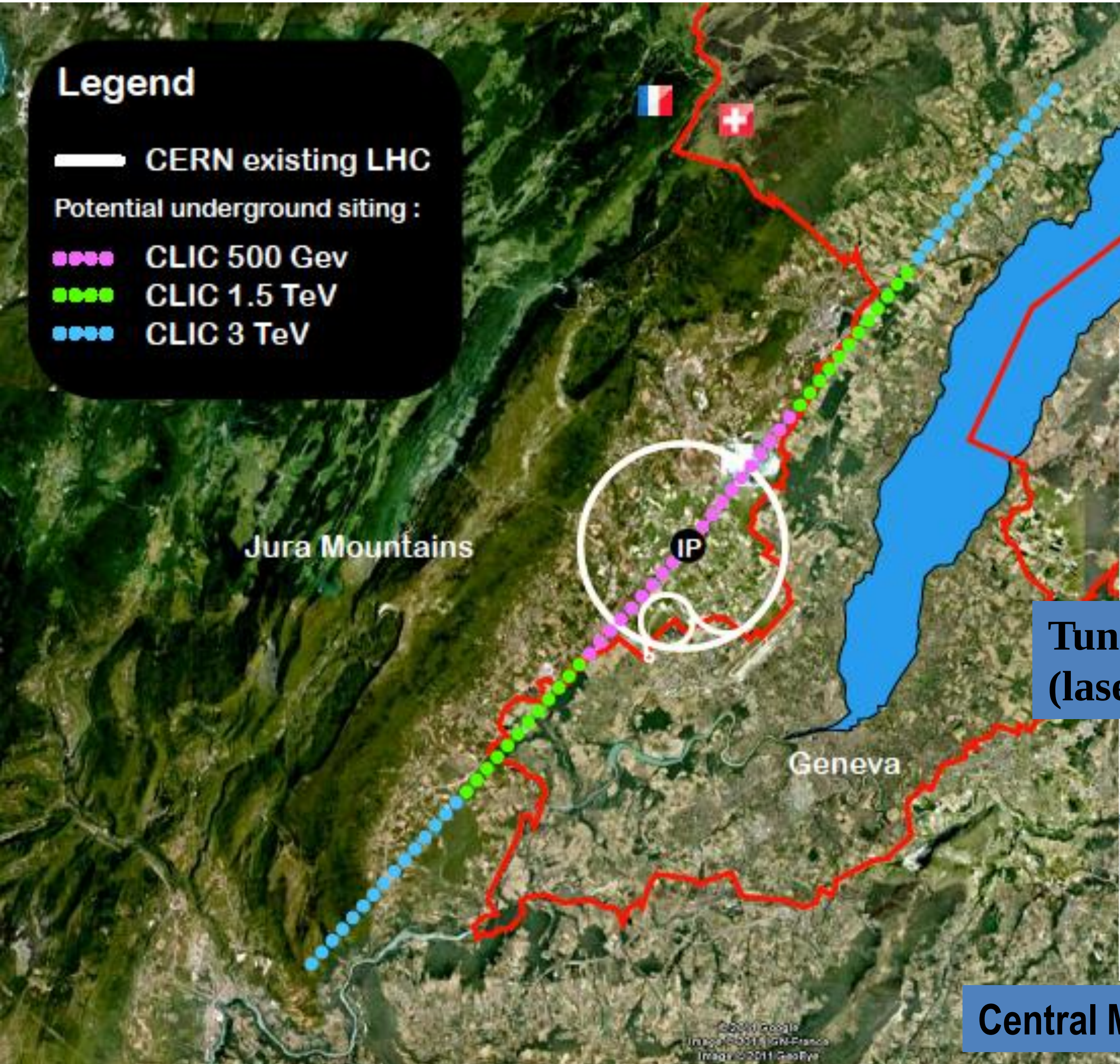
Measure Z (decays e.g. into $\mu^+\mu^-$), reconstruct Higgs "recoil" mass

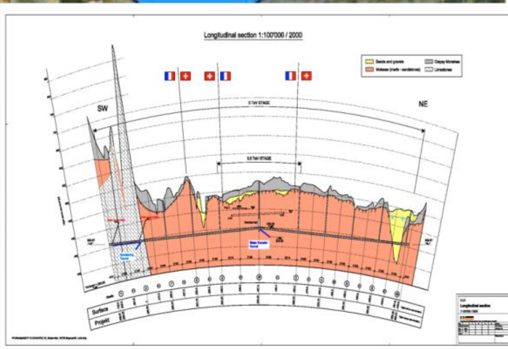
<u>**unique at Linear Collider:**</u>
since the initial state e^+e^- is very well defined,
this provides Higgs coupling to Z in a model-independent way

CLIC 500 GeV 0.5 ab^{-1}

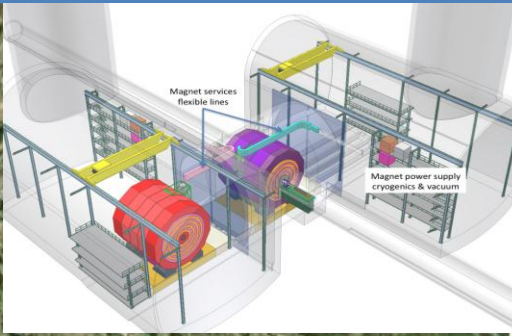


Simulations done before 4 July 2012 – assumed Higgs mass 120 GeV



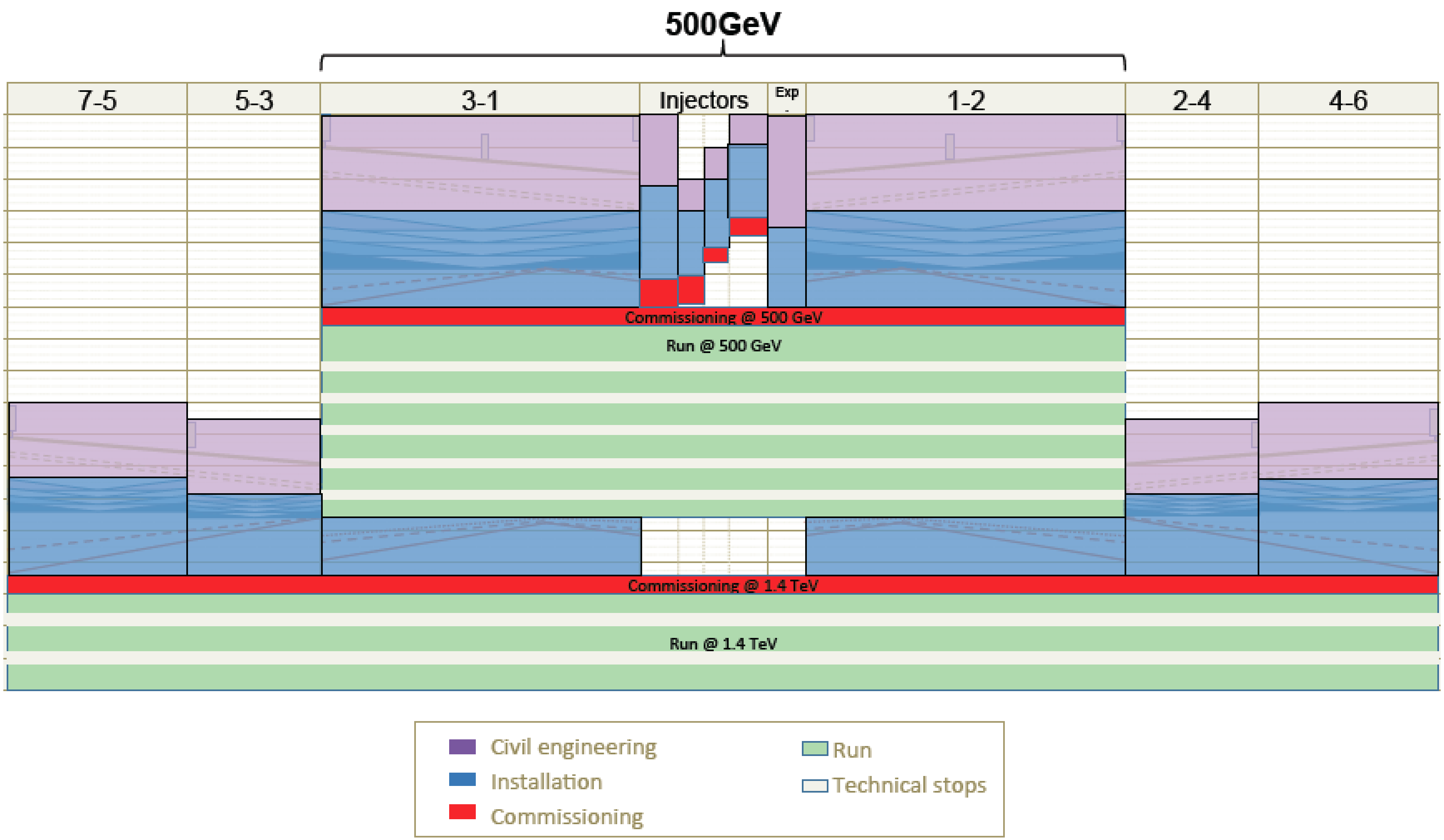


Tunnel implementations (laser straight)

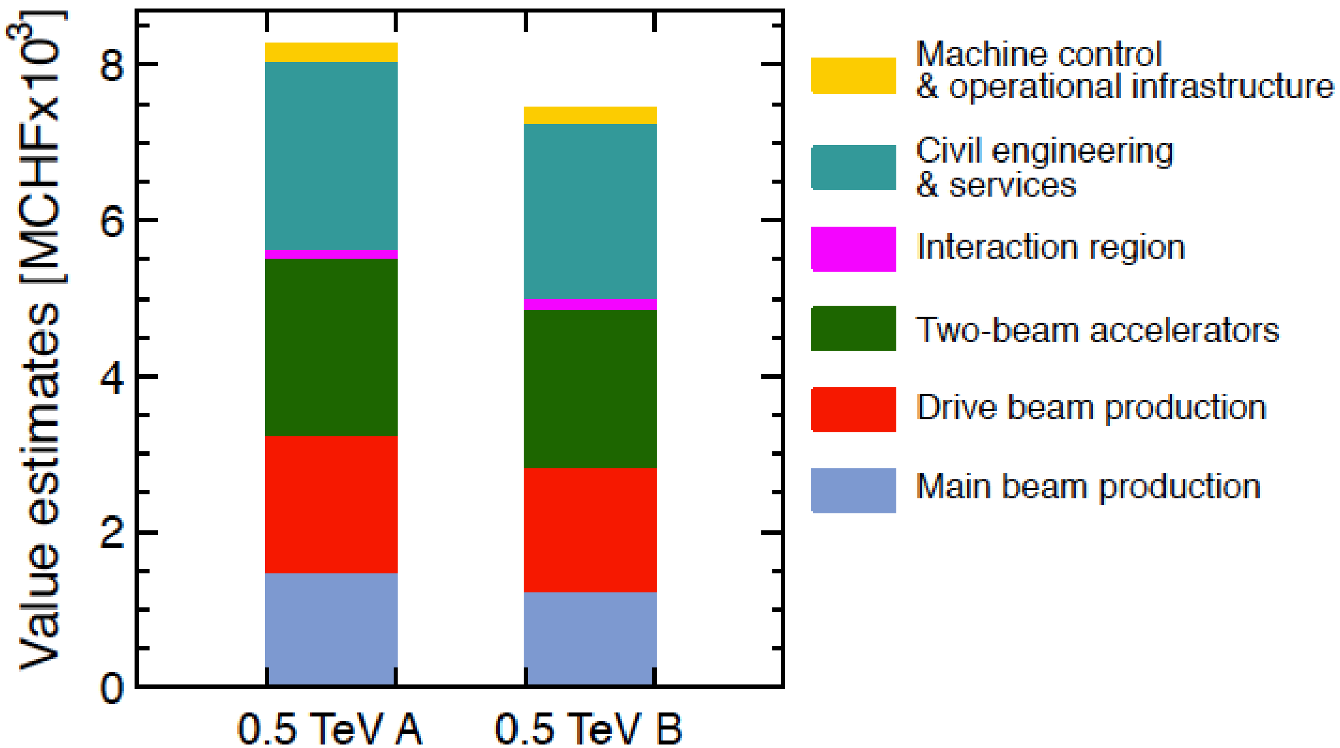


Central MDI & Interaction Region

Schedule first two stages



Costs



First to second stage: 4 MCHF/GeV (i.e. initial costs are very significant)

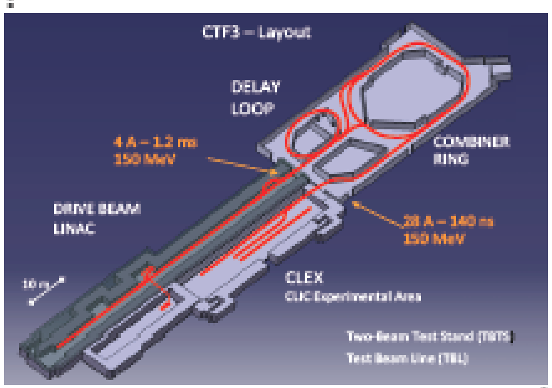
Caveats:

- Uncertainties 20-25%
- Possible savings around 10%
- However – first stage not optimised (work for next phase), parameters largely defined for 3 TeV final stage

CLIC project time-line

2012-16 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.



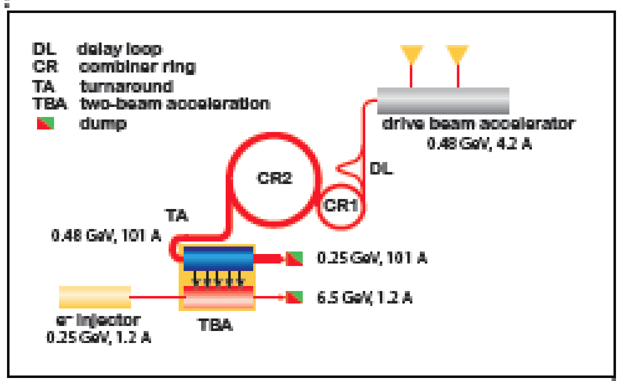
2016-17 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

2017-22 Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

Prepare detailed Technical Proposals for the detector-systems.



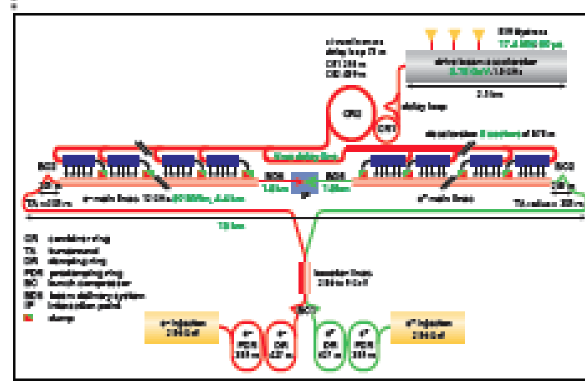
2022-23 Construction Start

Ready for full construction and main tunnel excavation.

2023-2030 Construction Phase

Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction.

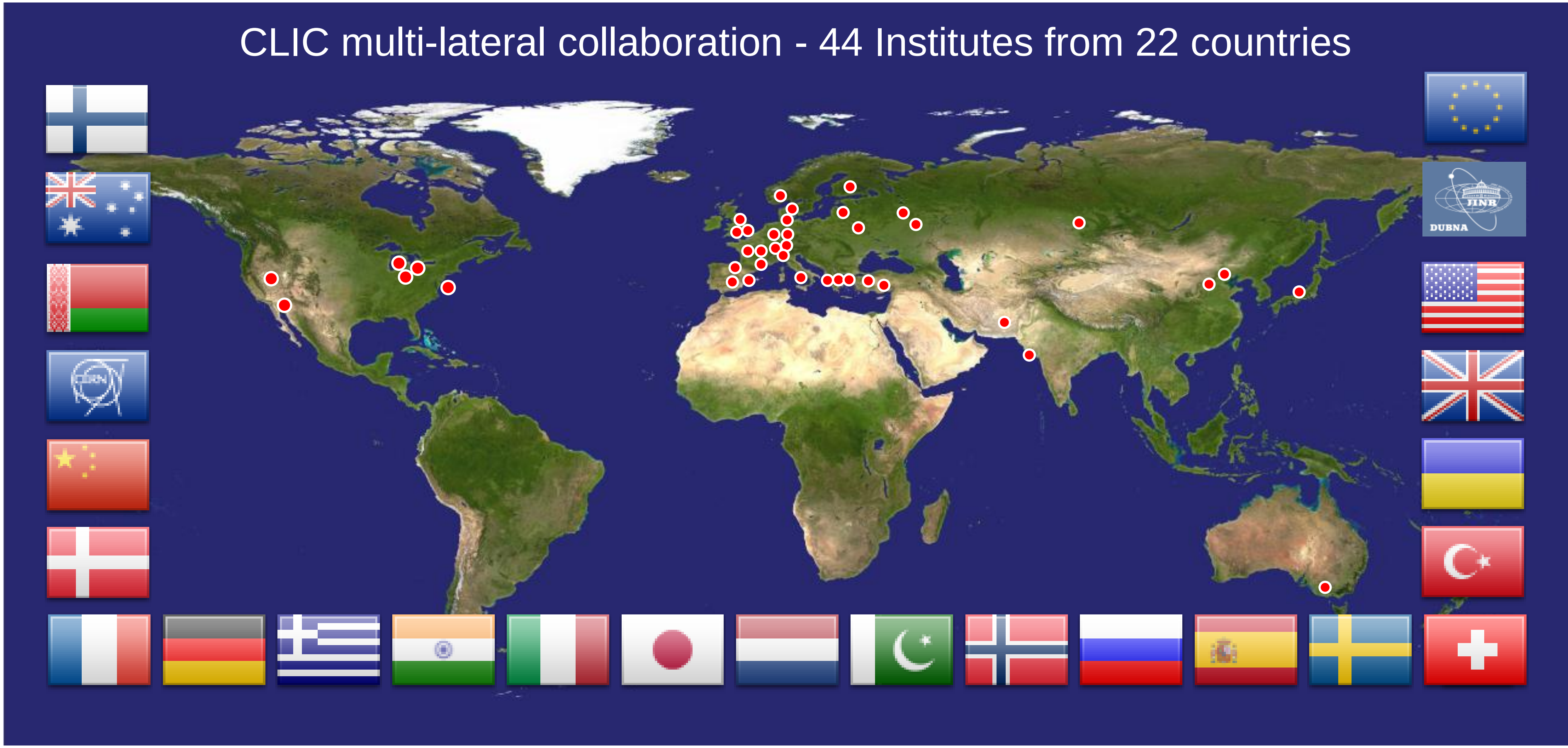
Preparation for implementation of further stages.



2030 Commissioning

From 2030, becoming ready for data-taking as the LHC programme reaches completion.

Current CLIC&CTF3 Collaboration



ACAS (Australia)
Aarhus University (Denmark)
Ankara University (Turkey)
Argonne National Laboratory (USA)
Athens University (Greece)
BINP (Russia)
CERN
CIEMAT (Spain)
Cockcroft Institute (UK)
ETH Zurich (Switzerland)
FNAL (USA)
Gazi Universities (Turkey)
Helsinki Institute of Physics (Finland)
IAP (Russia)
IAP NASU (Ukraine)
IHEP (China)
INFN / LNF (Italy)
Instituto de Fisica Corpuscular (Spain)
IRFU / Saclay (France)
Jefferson Lab (USA)
John Adams Institute/Oxford (UK)
Joint Institute for Power and Nuclear Research SOSNY /Minsk (Belarus)
John Adams Institute/RHUL (UK)
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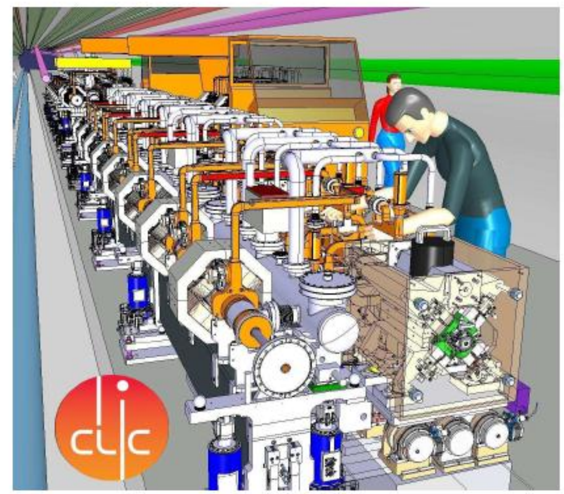
Polytech. Univ. of Catalonia (Spain)
PSI (Switzerland)
RAL (UK)
RRCAT / Indore (India)
SLAC (USA)
Sincrotrone Trieste/ELETTRA (Italy)
Thrace University (Greece)
Tsinghua University (China)
University of Oslo (Norway)
University of Vigo (Spain)
Uppsala University (Sweden)
UCSC SCIPP (USA)

For more information about the project

http://clic-study.org/accelerator/CLIC-ConceptDesignRep.php

SLAC-R-985
KEK Report 2012-1
PSI-12-01
JAI-2012-001
CERN-???
13 September 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

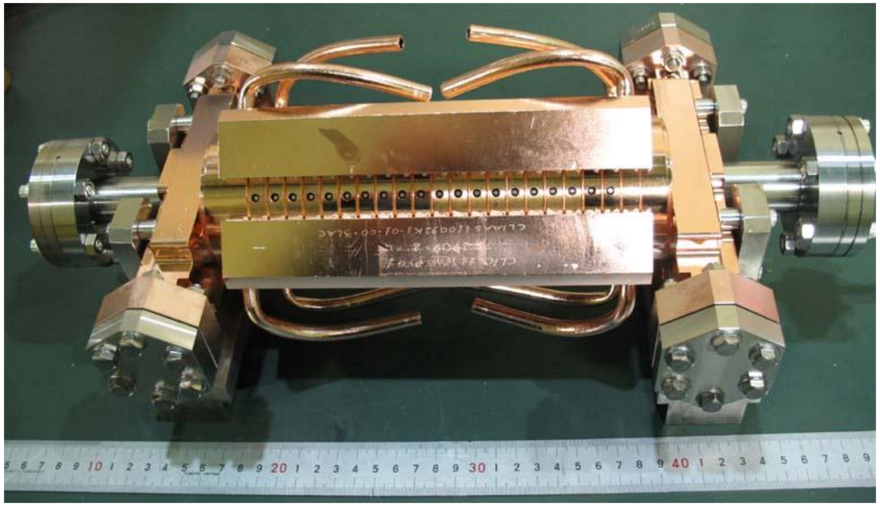


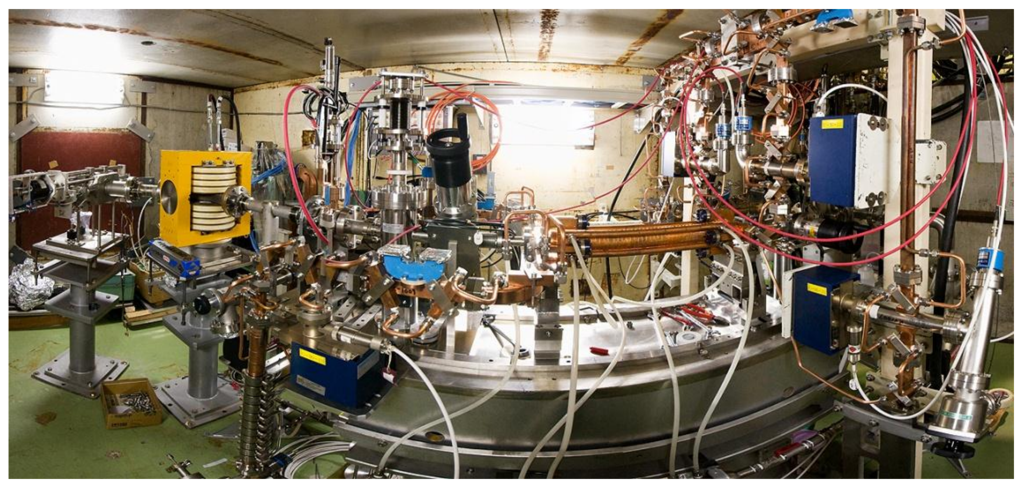
A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

High-gradient structure testing

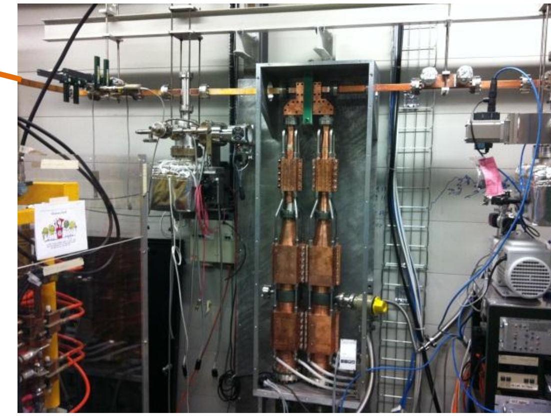




J. Kovermann

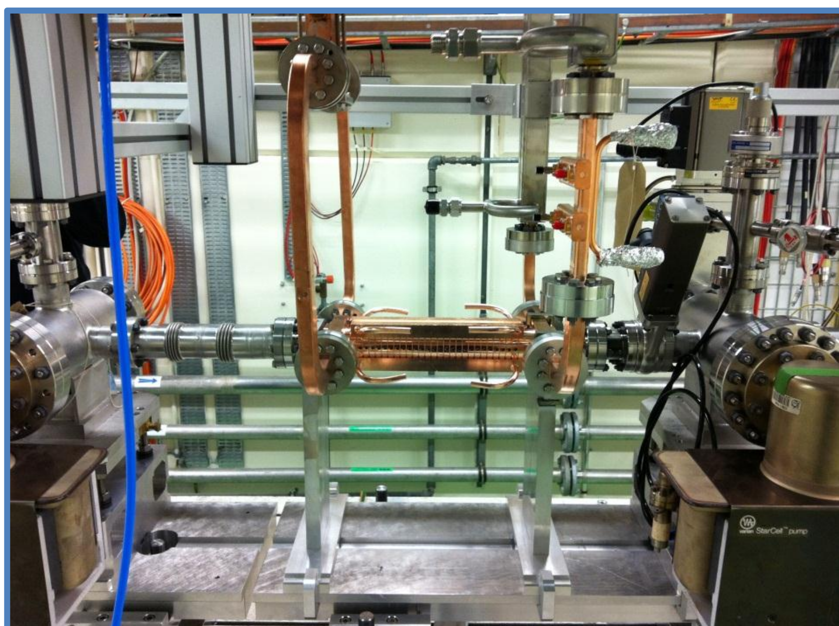
Status of the Xbox1

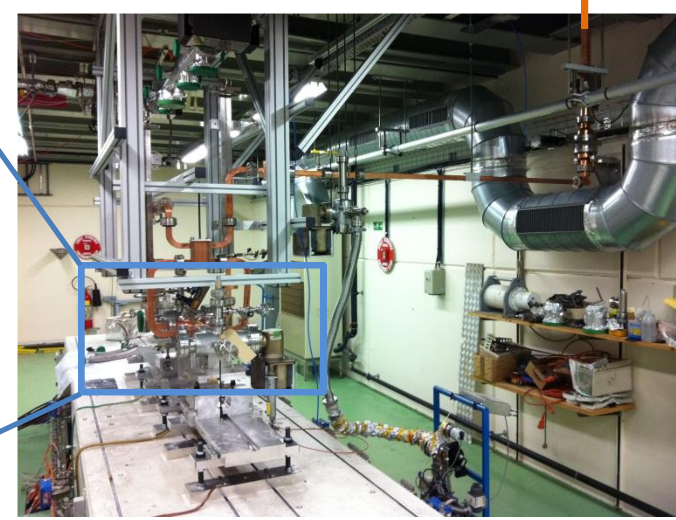
- WG network and LLRF finished
- Final vacuum infrastructure installation end of June
- Modulator flat top tuning by Scandinova done
- Klystron conditioned up to 40MW, 500ns, 50Hz with loads (50MW, 300ns, 50Hz)
- Pulse compressor operation started



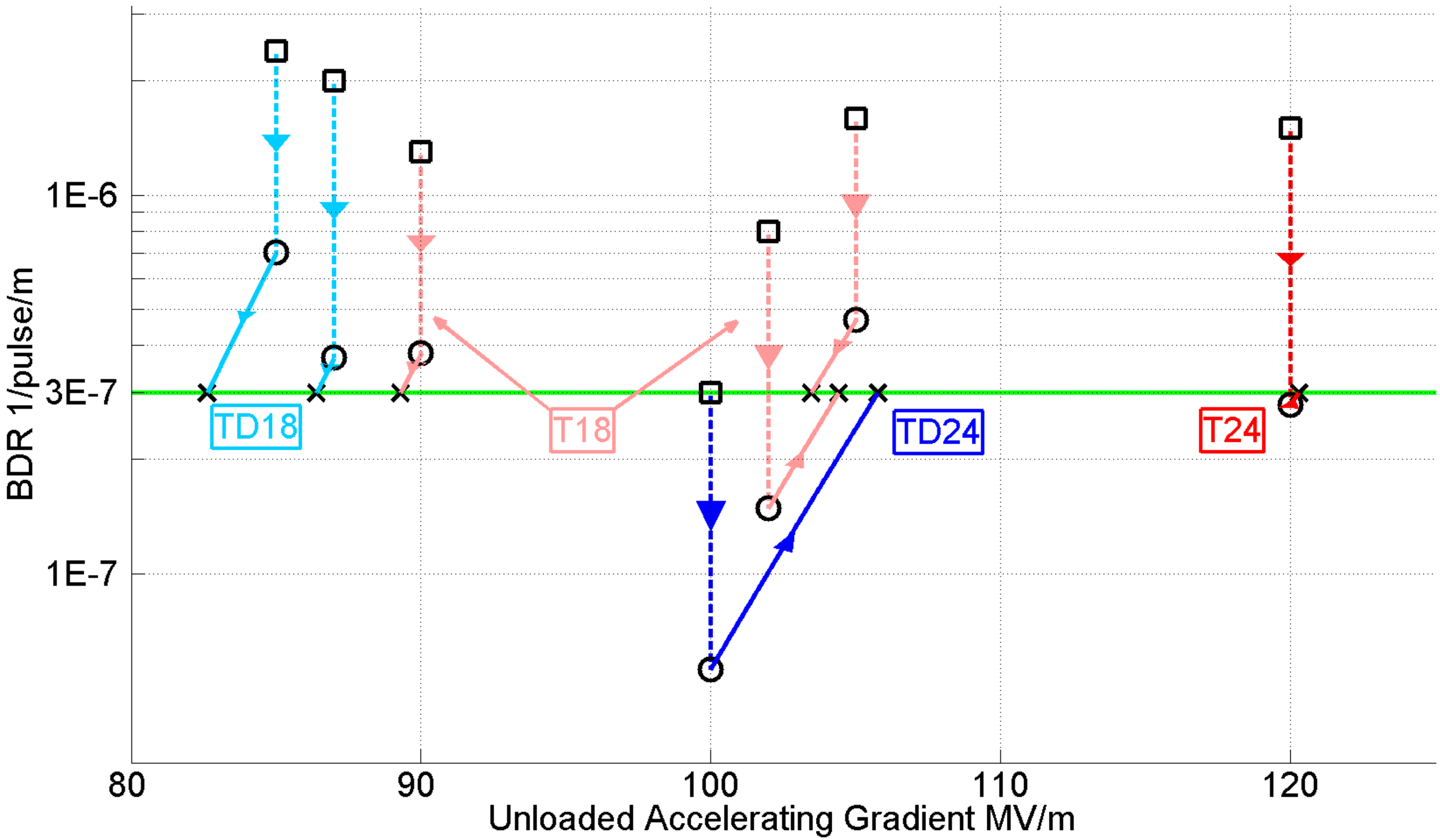
Gallery

Bunker





Accelerating gradient test status: 4-9-2012



High-power design criteria

The functions which, along with surface electric field and magnetic field (pulsed surface heating), give the high-gradient performance of the structures are:

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

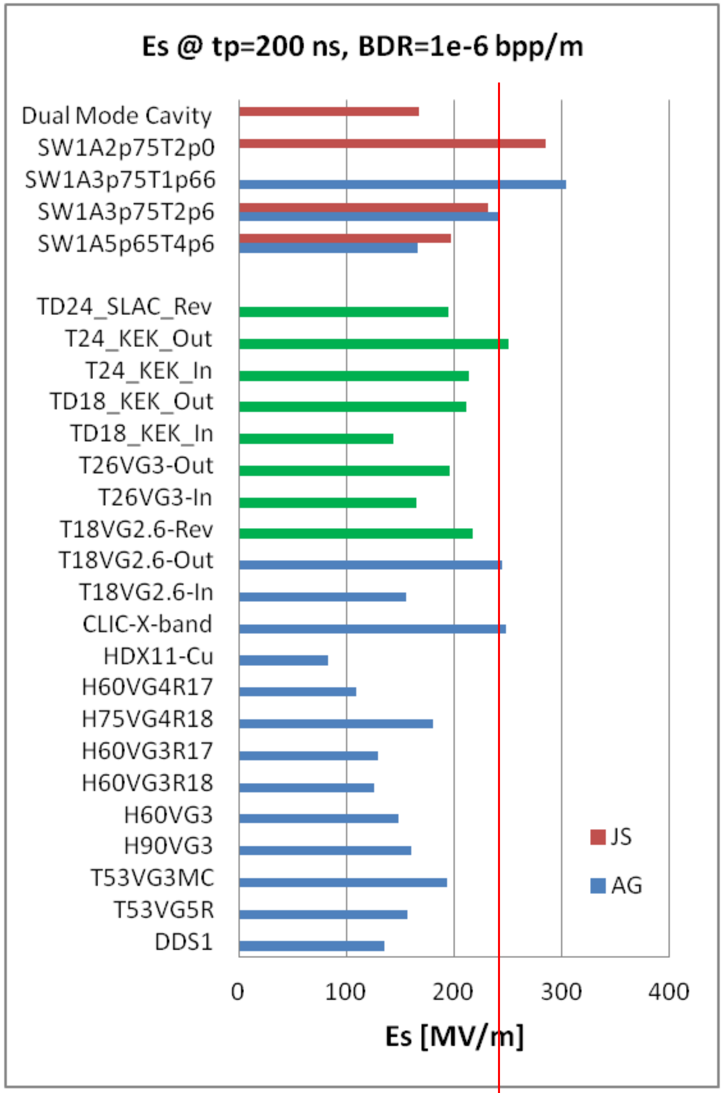
global power flow

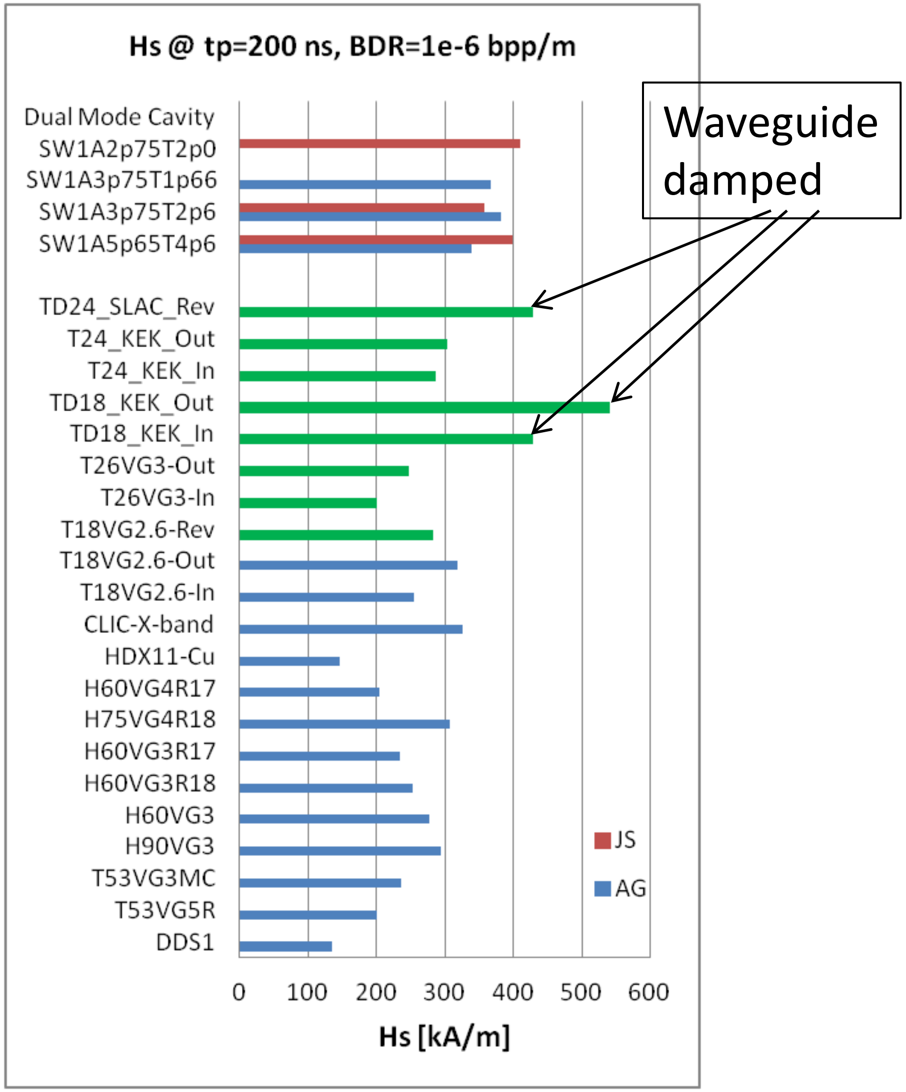
$$S_c = \mathrm{Re}(\mathbf{S}) + \frac{1}{6}\mathrm{Im}(\mathbf{S})$$

local complex power flow

These are now standard design criteria used throughout the CLIC structure program. We are actively pursuing checking their validity over a wider range of parameters and putting them on a more solid footing.

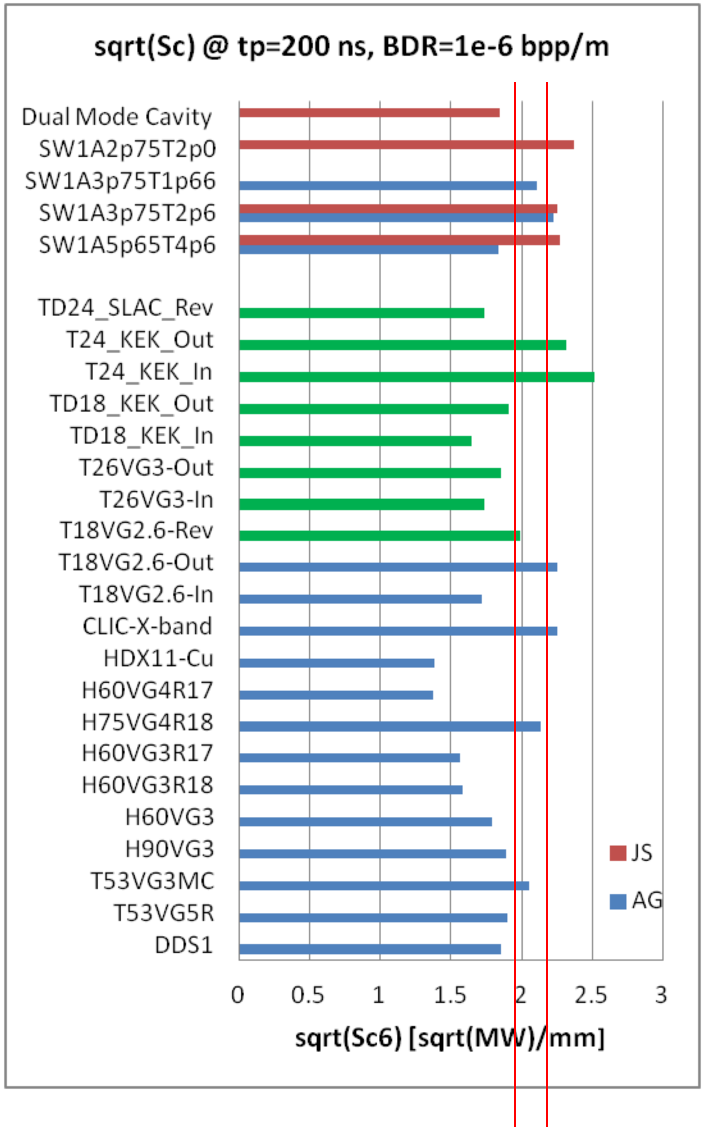
Maximum surface electric and magnetic fields

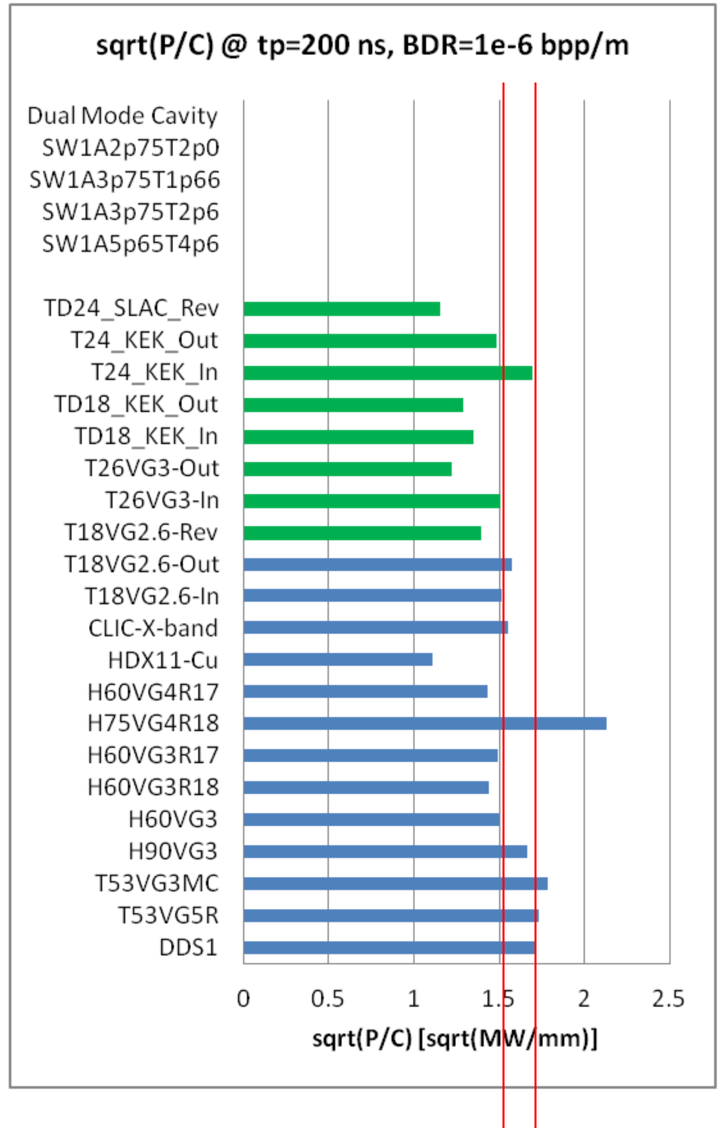




Es = 250 MV/m or higher has been achieved in several cases: very low or zero group velocity

Power flow related quantities: Sc and P/C





$Sc = 4 - 5\ MW/mm^2$

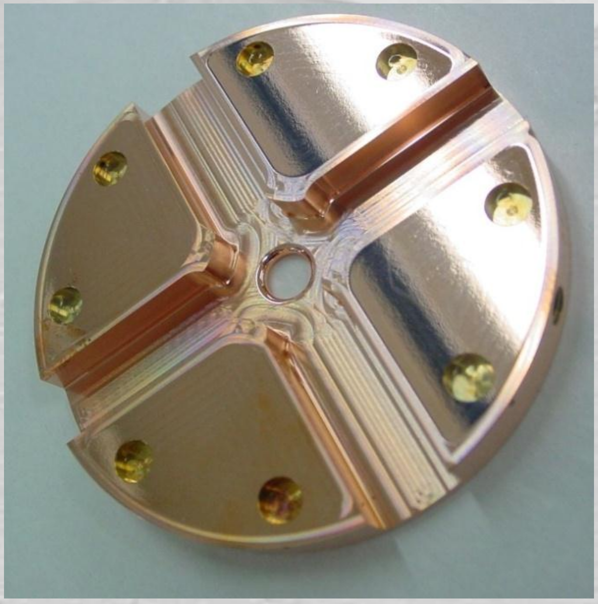
$P/C = 2.3 – 2.9\ MW/mm$

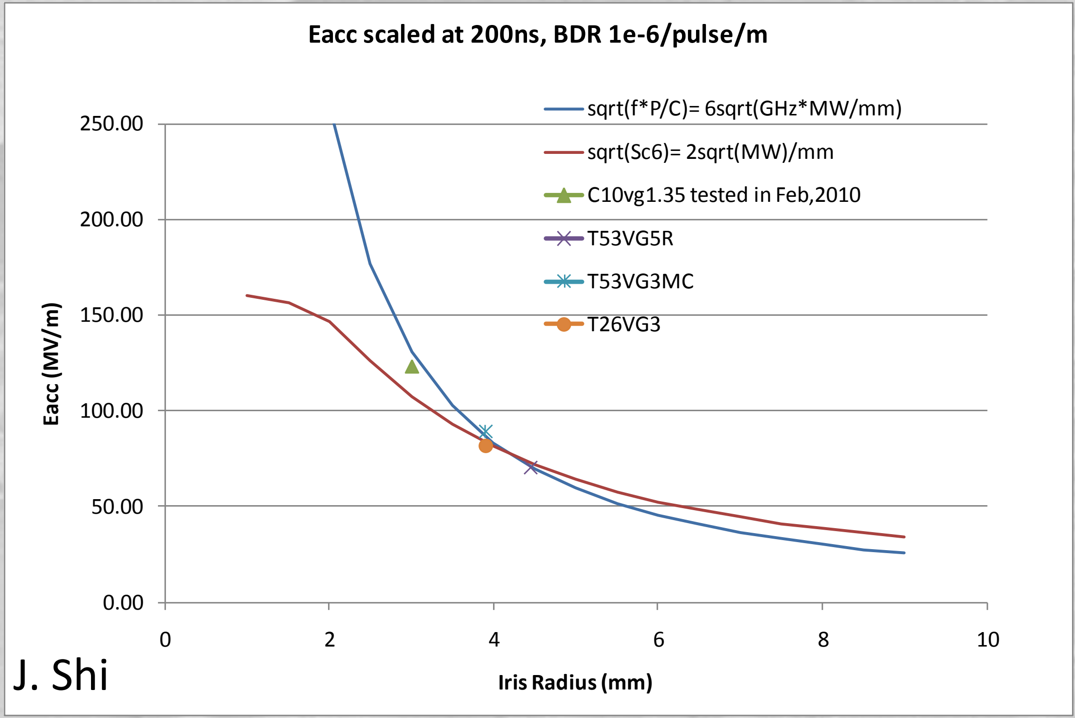
CLIC Accelerating structure specifications

Beam dynamics:

1. 5.8 mm diameter minimum average aperture (short range transverse wake)
2. < 1 V/pC/mm/m long-range transverse wakefield at second bunch (approximately x50 suppression).

$$W_t \propto a^3$$ but

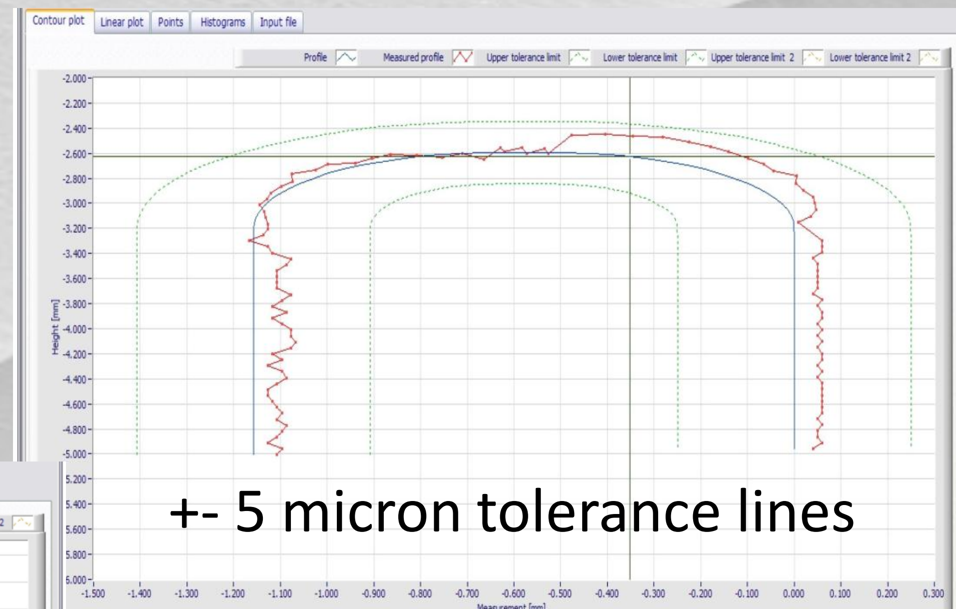




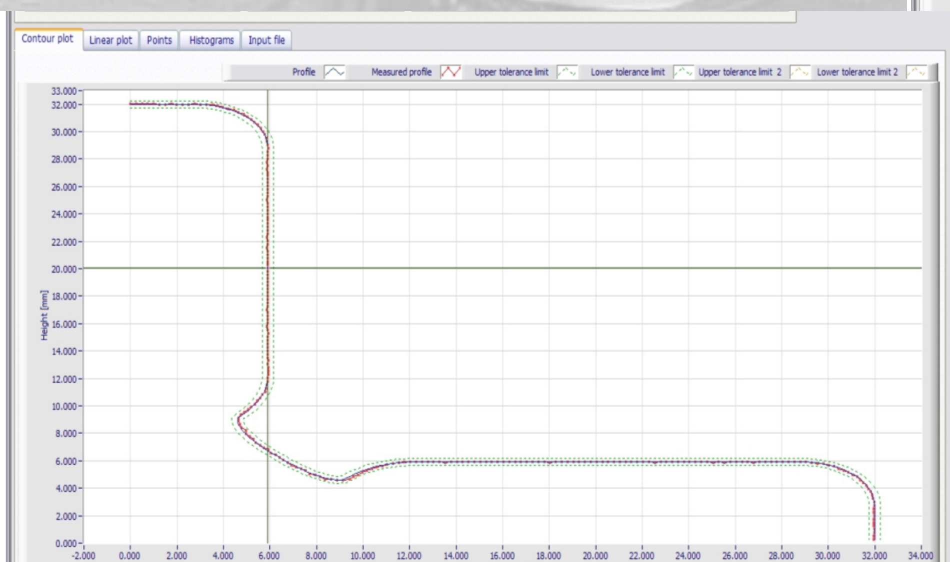
How to make 'em

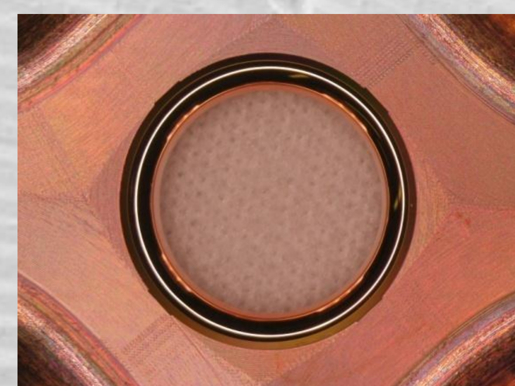
Machining: OFHC copper diamond milled and turned disks with micron precision.

G. Riddone, S. Atieh



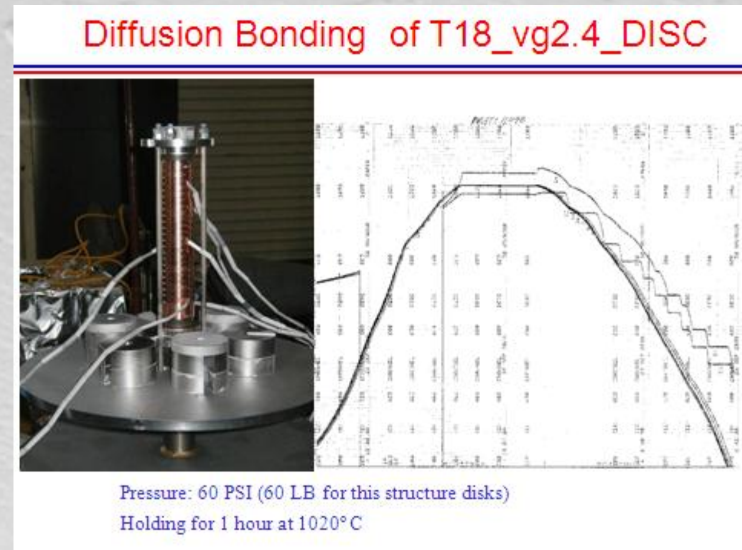
+- 5 micron tolerance lines



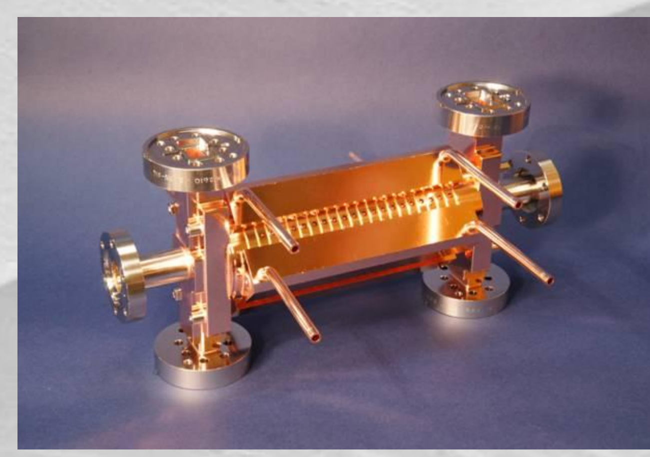


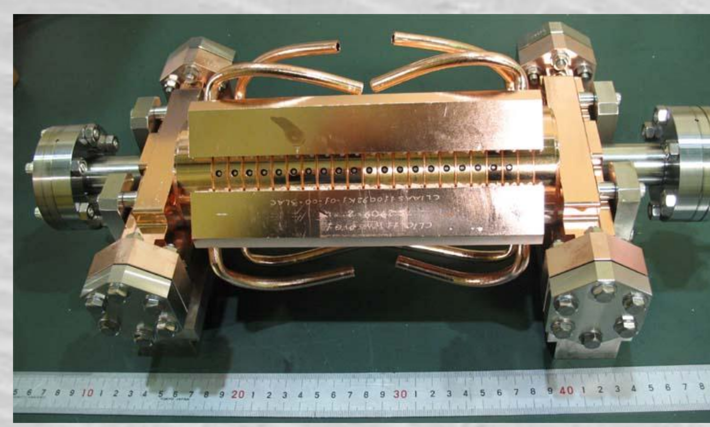
Accelerating structures – manufacture

Stacking disks



Temperature treatment for high-gradient





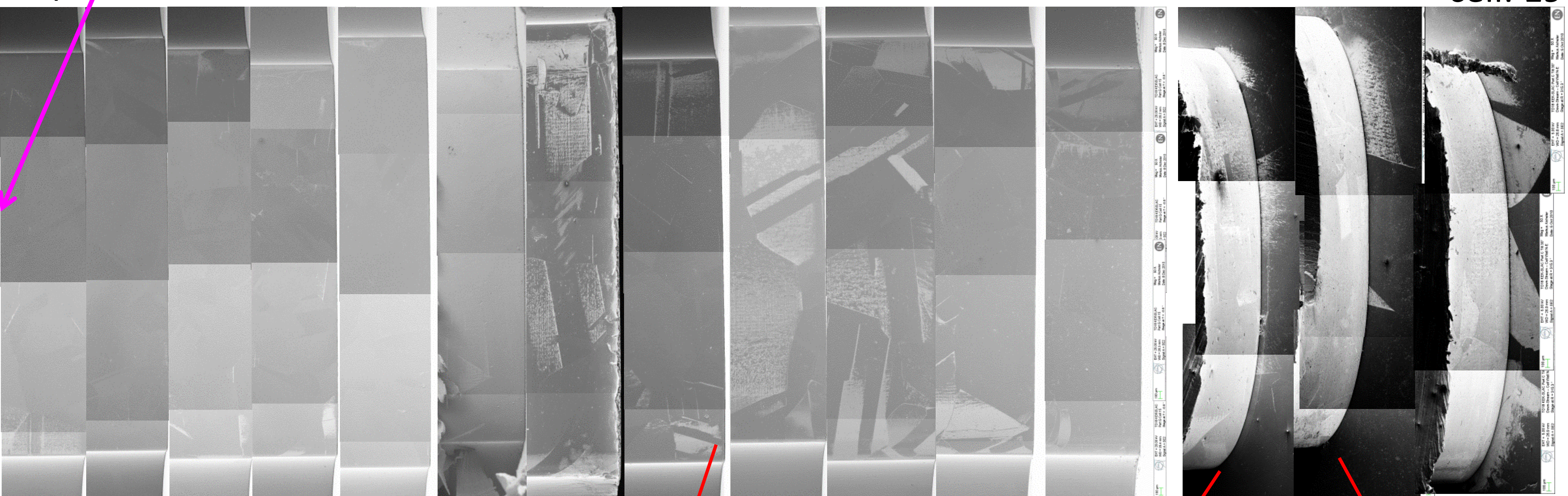
Structures ready for test

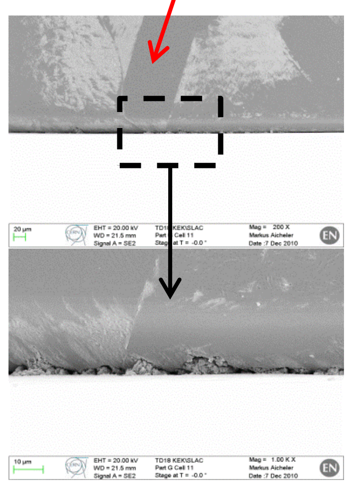
TD24

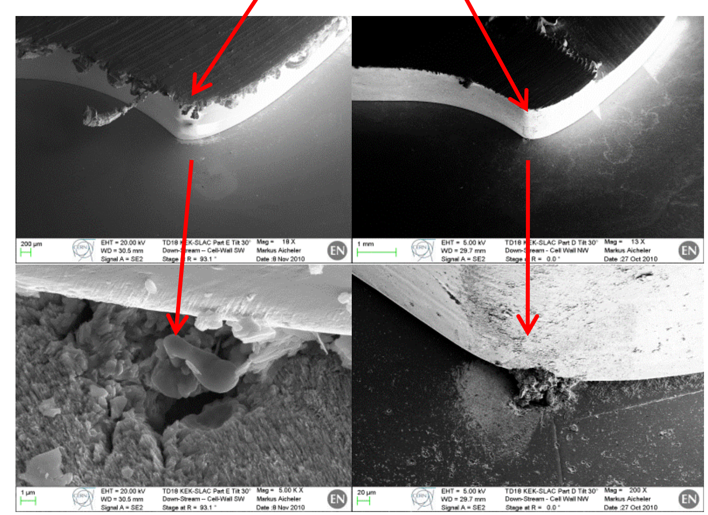
The effect of surface currents

Cell # (cell #1 is a input matching cell):

4 5 6 7 8 9 10 11 12 13 14 15 ?16? 17 18 Last regular cell: 19







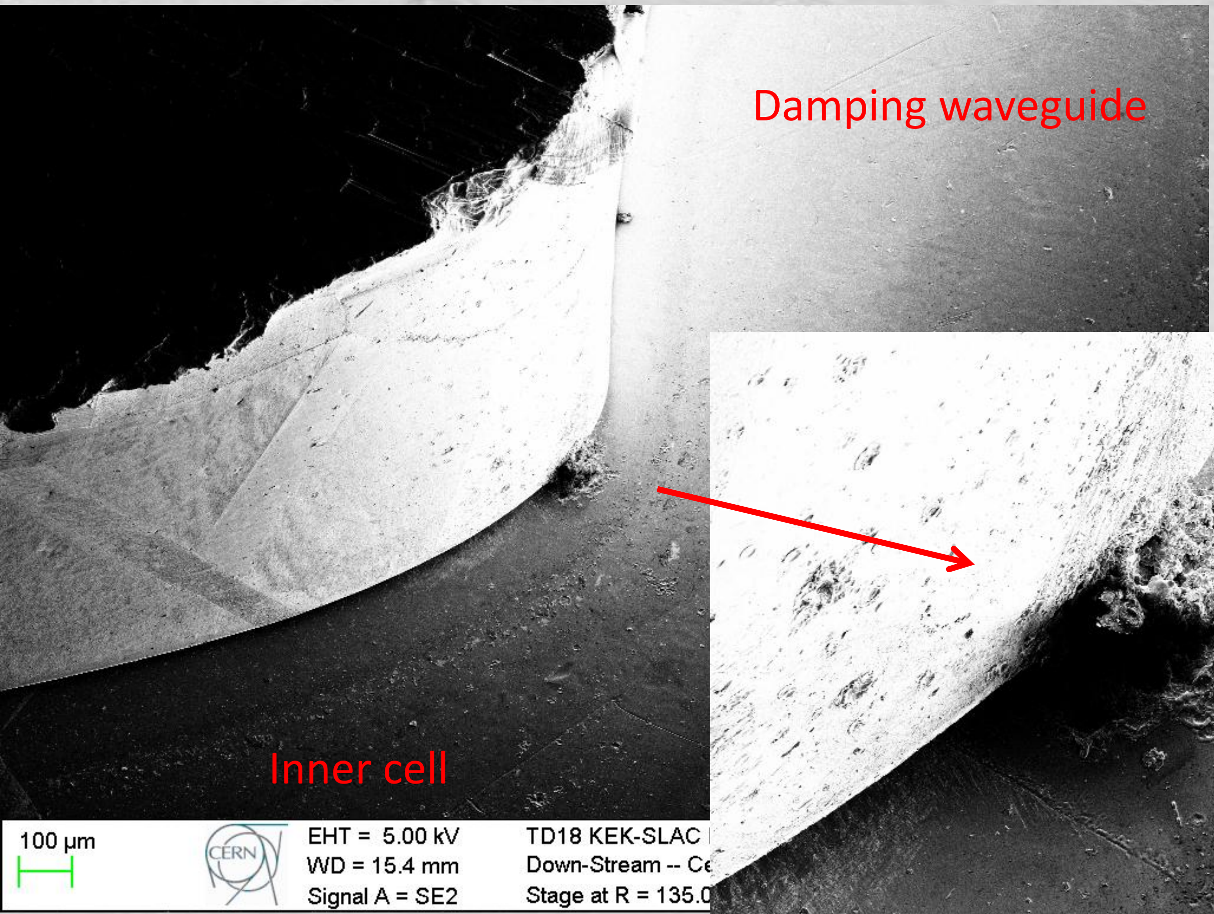
It seems that cell #10 (regular cell #9 ~ **middle cell**) exhibits the level of damage which could be considered as **a limit.**

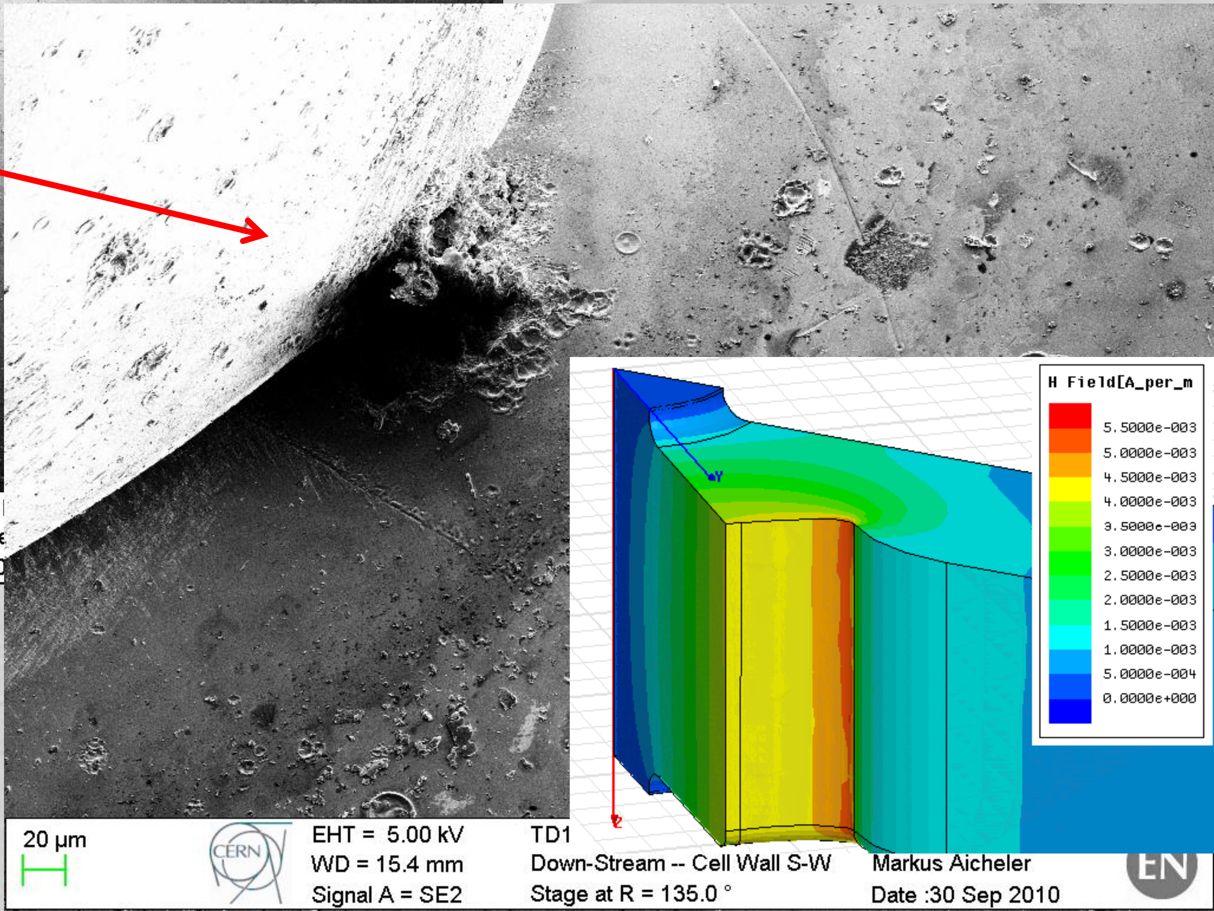
A. Grudiev

Images courtesy of M. Aicheler: http://indico.cern.ch/getFile.py/access?contribId=0&resId=1&materialId=slides&confId=106251

Features in high current region of TD18

Current density around $2x10^8 A/cm^2$ during test



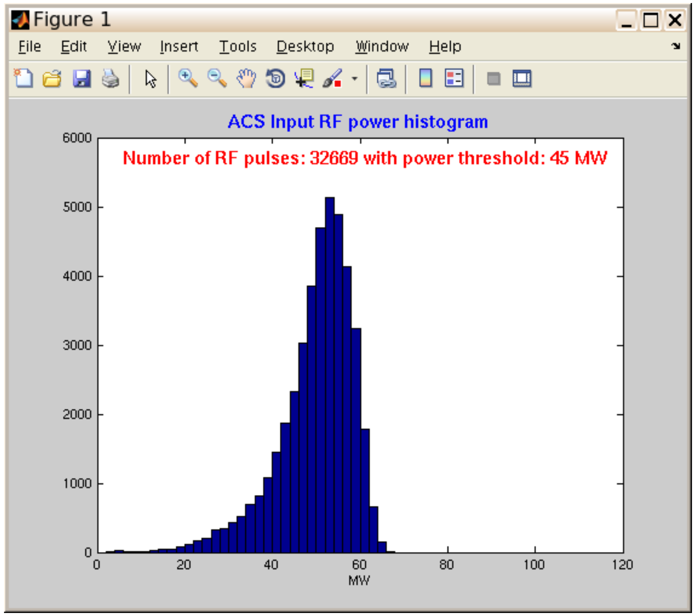


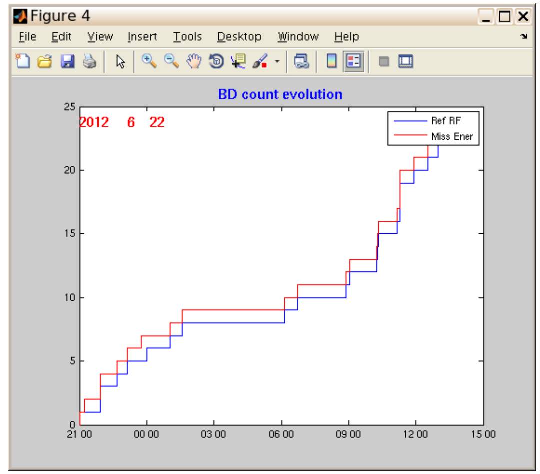
Breakdowns follow Poisson statistics

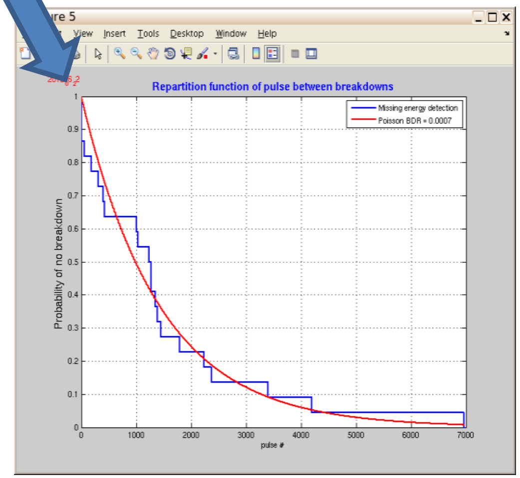
BD studies in TBTS

One of the first nights of TBTS operation

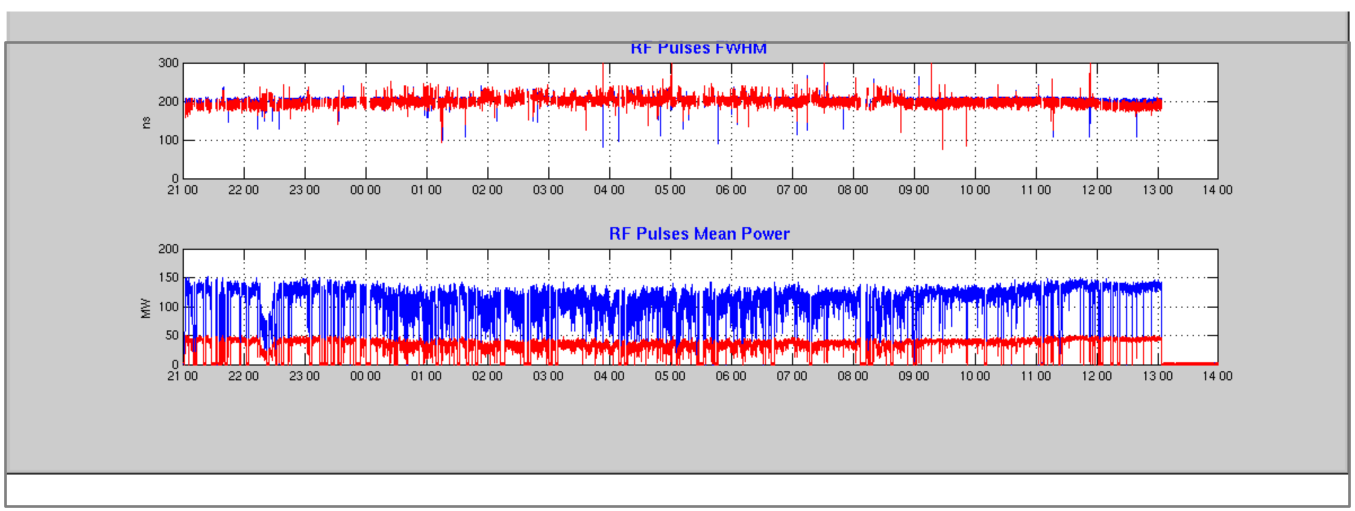
BDR ≈$7\ 10^{-4}$



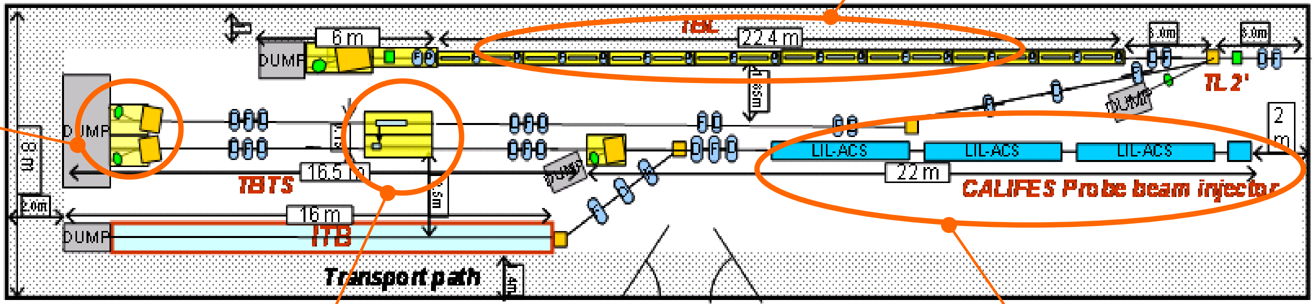


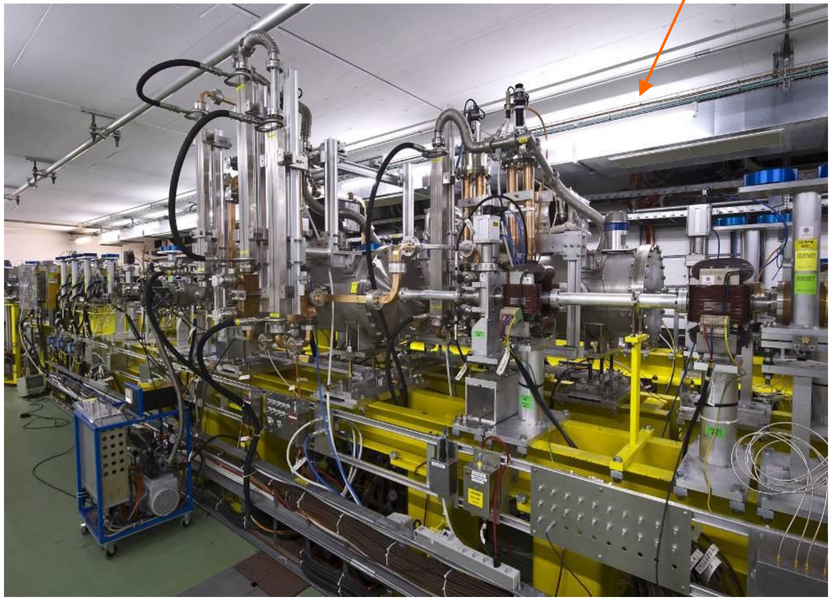


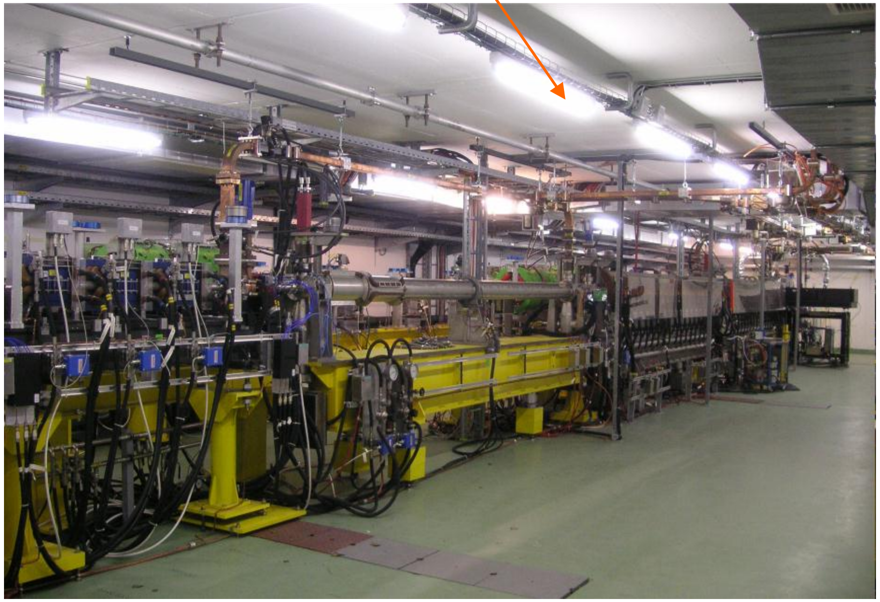
W. Farabolini



TBTS is the test area in CLEX, where feasibility of the CLIC two beam acceleration scheme is…already demonstrated (not yet at a nominal 100 MV/m accelerating gradient).

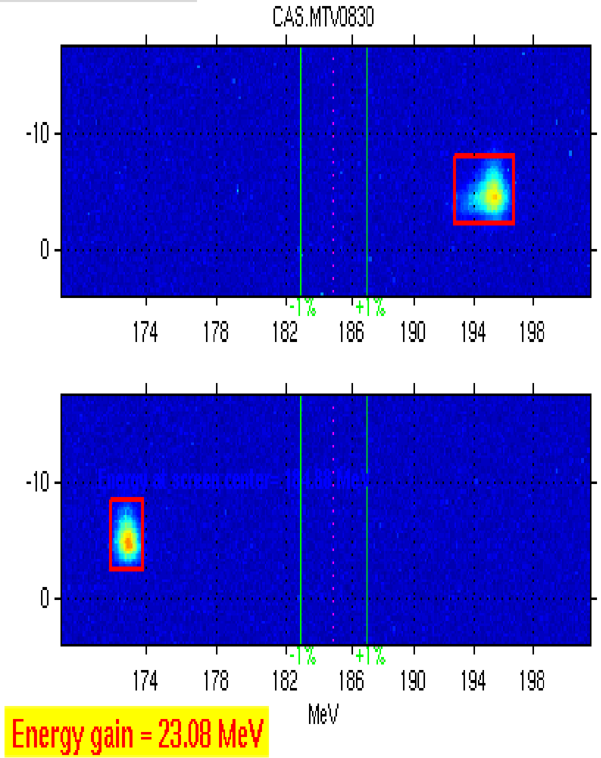


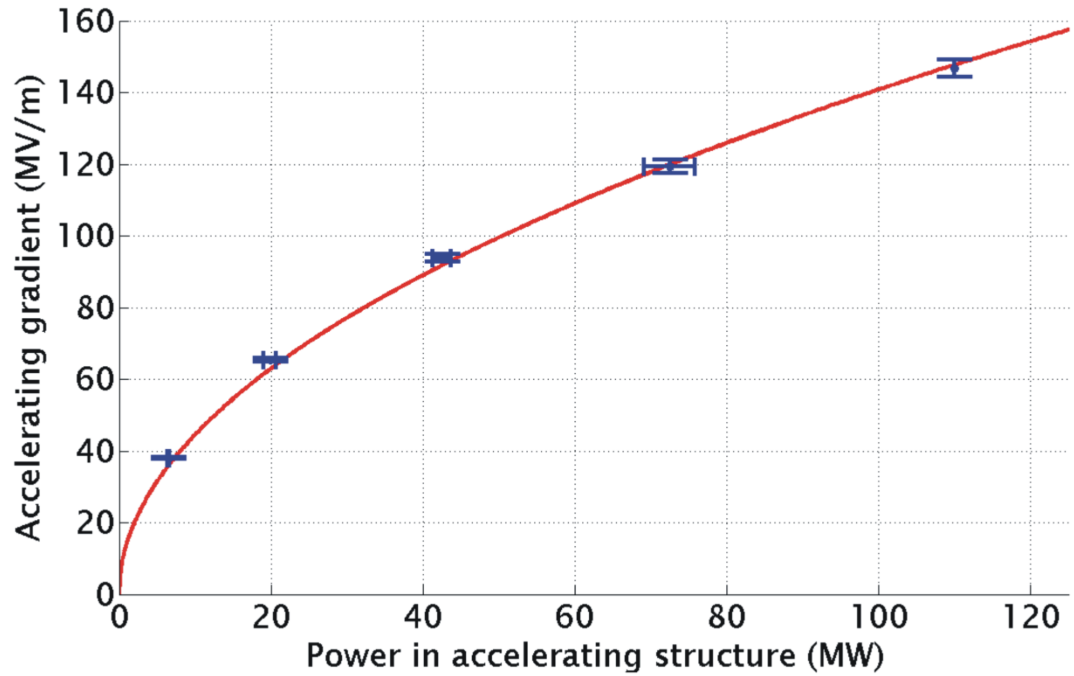




TBTS: Two Beam Acceleration

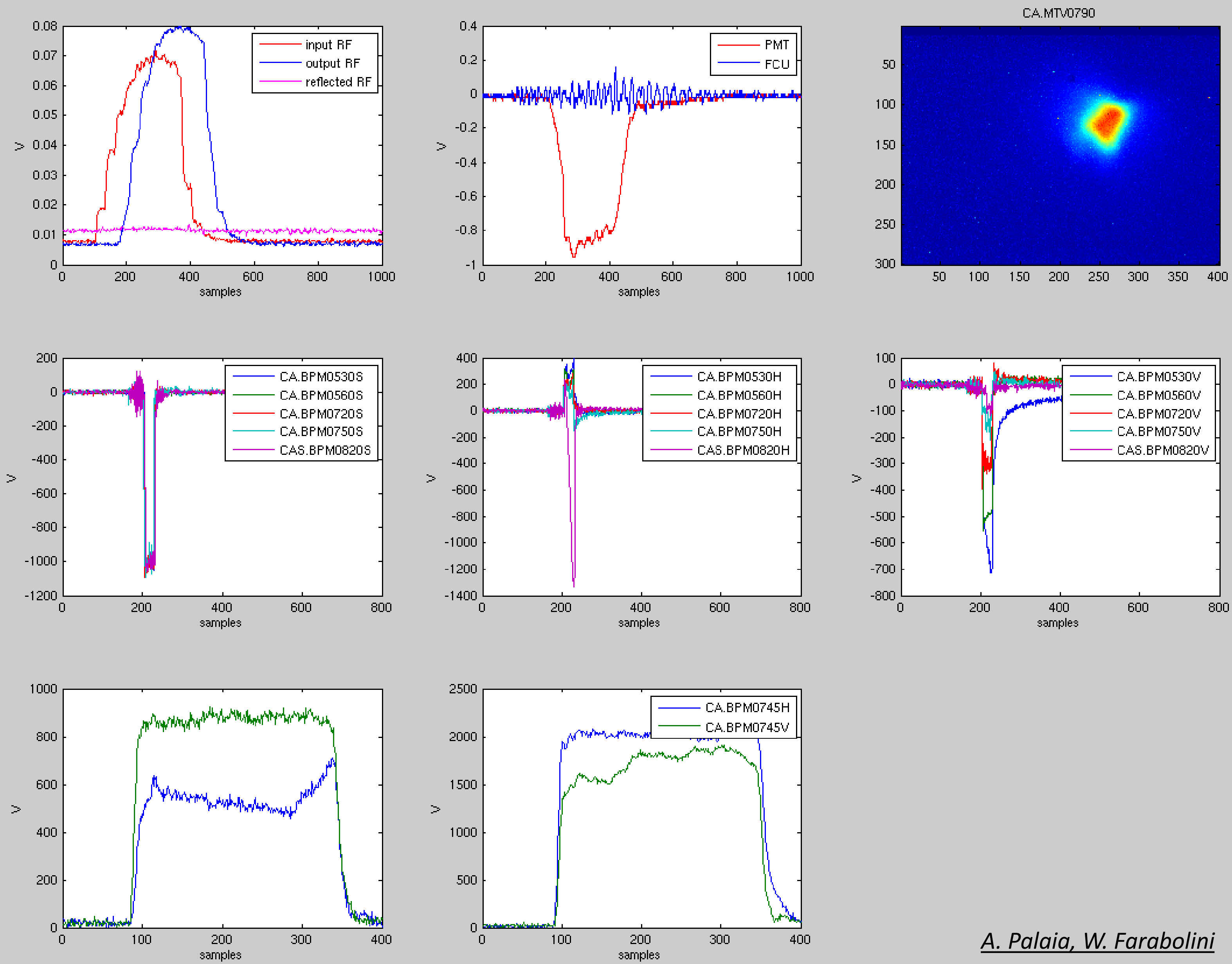
CTF3 team



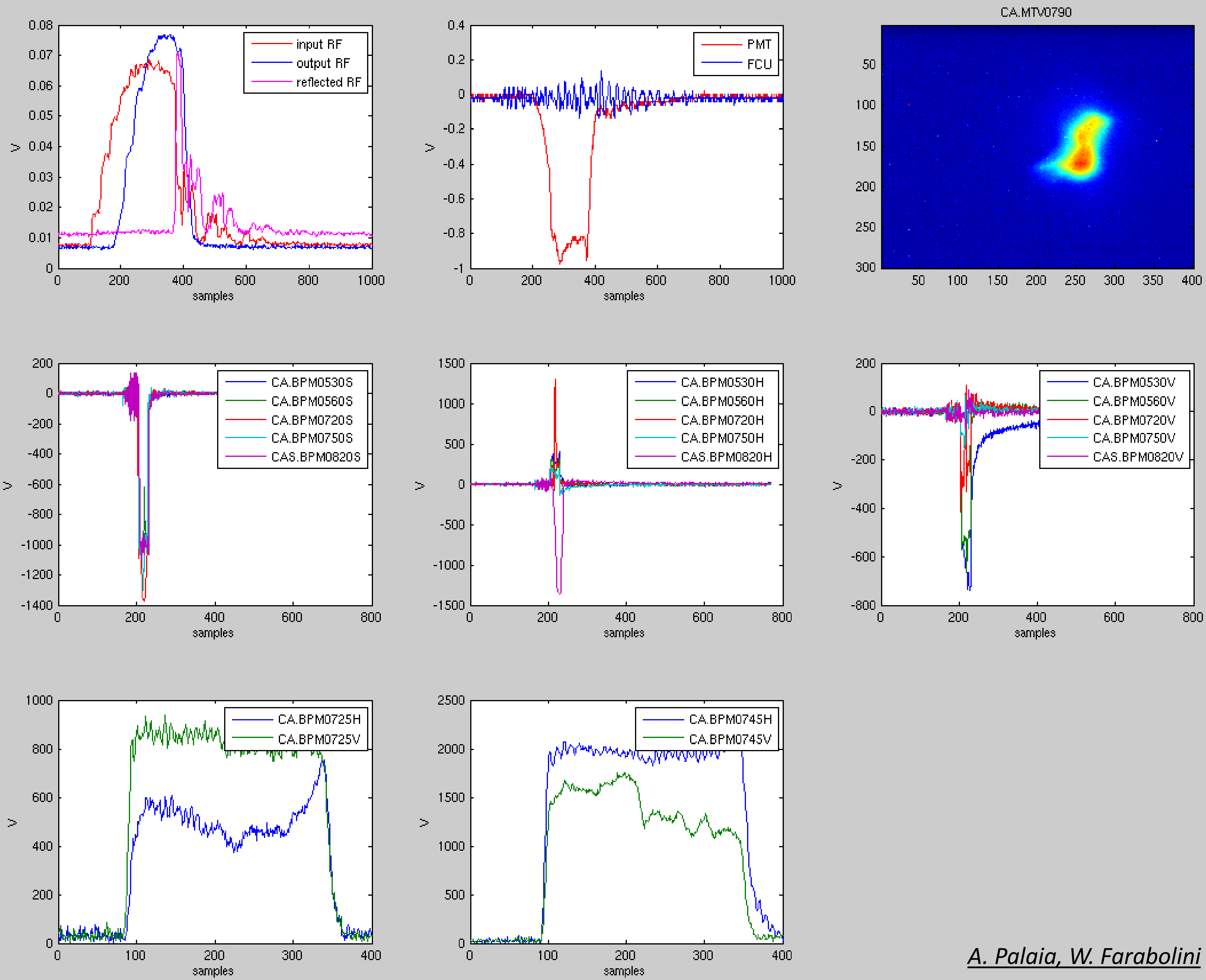


Maximum gradient
145 MV/m

Consistency between
- produced power
- drive beam current
- test beam acceleration



A. Palaia, W. Farabolini

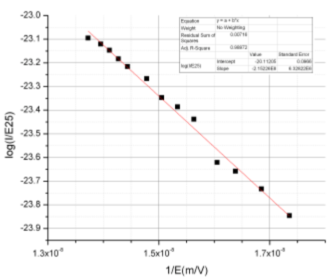


A. Palaia, W. Farabolini

Investigation of locally lower work function

Electron emission

$I_{FN}\ (\beta, \phi_0, A_e, E_0)$



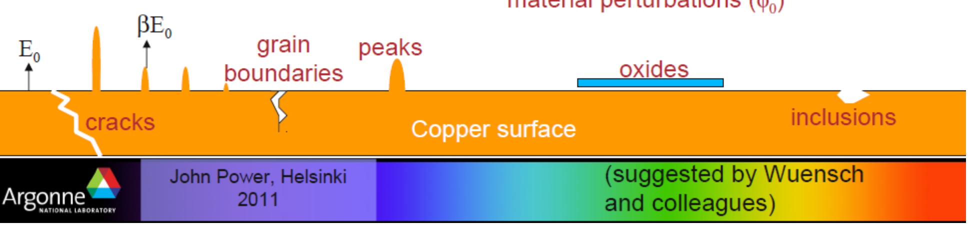
Fowler Nordheim Law (RF fields):

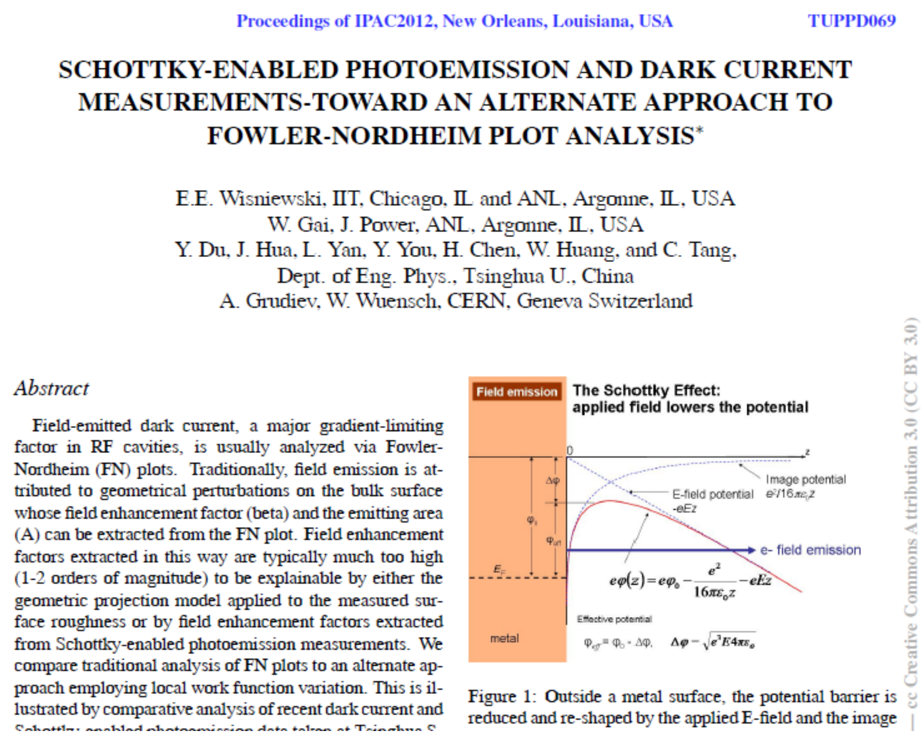
$$\bar{I} = \frac{5.79\times10^{-12}\exp(9.35\varphi_0^{-0.5})A_e(\beta E_0)^{2.5}}{\varphi_0^{1.75}}\exp\left(\frac{-6.53\times10^{9}\varphi_0^{1.5}}{\beta E_0}\right)$$

1. High field enhancements (β) can cause field emission.
2. Low work function (ϕ_0) in small areas can cause field emission.

typical picture ➔
geometric perturbations (β)

alternate picture ➔
material perturbations (ϕ_0)





Proceedings of IPAC2012, New Orleans, Louisiana, USA TUPPD069

SCHOTTKY-ENABLED PHOTOEMISSION AND DARK CURRENT MEASUREMENTS-TOWARD AN ALTERNATE APPROACH TO FOWLER-NORDHEIM PLOT ANALYSIS*

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Abstract

Field-emitted dark current, a major gradient-limiting factor in RF cavities, is usually analyzed via Fowler-Nordheim (FN) plots. Traditionally, field emission is attributed to geometrical perturbations on the bulk surface whose field enhancement factor (beta) and the emitting area (A) can be extracted from the FN plot. Field enhancement factors extracted in this way are typically much too high (1-2 orders of magnitude) to be explainable by either the geometric projection model applied to the measured surface roughness or by field enhancement factors extracted from Schottky-enabled photoemission measurements. We compare traditional analysis of FN plots to an alternate approach employing local work function variation. This is illustrated by comparative analysis of recent dark current and Schottky-enabled photoemission data taken at Tsinghua S...

Figure 1: Outside a metal surface, the potential barrier is reduced and re-shaped by the applied E-field and the image

Experiment starting at CERN in photocathode lab

The big questions for accelerator high gradients

- Why do we see a reduced gradient in waveguide damped structures? Electromigration?
- What is driving the dependency of breakdown rate on gradient and pulse length? The evolution of the surface and creation of field emitters, the transition of field emitter to breakdown site or whether a breakdown runs away or not.
- What is the physics which drives high-power rf scaling law, in our opinion S_c? In other words, how can the maximum surface electric field in an rf structure depend on the macroscopic geometry of the system? For example is it through the presence of a magnetic field or for example does the breakdown "feel" the group velocity during the breakdown transient?
- How does a structure condition? How can we prepare structures to minimize it? Why does our fabrication procedure work?
- What happens when we load the structures with beam and change the field distribution inside?

New Directions

With steady progress demonstrating the CLIC baseline structure we are now asking - what other applications could benefit from our developments? Because:

- Spreading the technology will broaden and strengthen the technological base which would one day be needed to support construction of a linear collider.
- It's a new challenge plus it would feel nice to see our ideas on a timescale shorter than that of a linear collider.

Among the application which would benefit from our high-gradient technology:

- **Linacs for proton and carbon ion cancer therapy.**
- High repetition rate FELs (Free Electron Lasers) for the 'photon-science' community which encompasses biology, chemistry, material science and many other fields.
- Compton-scattering gamma ray sources providing MeV-range photons for laser-based nuclear physics (nuclear-photonics) and fundamental processes (QED studies for example). There are also potential applications such as nuclear resonance fluorescence for isotope detection in shipping containers and mining.

Applying high-gradient to medical linacs

If our theoretical models are correct we should be able to increase gradient for medical proton therapy linacs up to around 50 MV/m from the current 27 MV/m in LIBO linac tanks (in CABOTO, the medical linac designed by the TERA foundation)**.**

We wish to do this for specific a target application so - design, build and high-power test two accelerating structures targeting use in TULIP, an idea of Ugo Amaldi which is being studied by the TERA foundation.

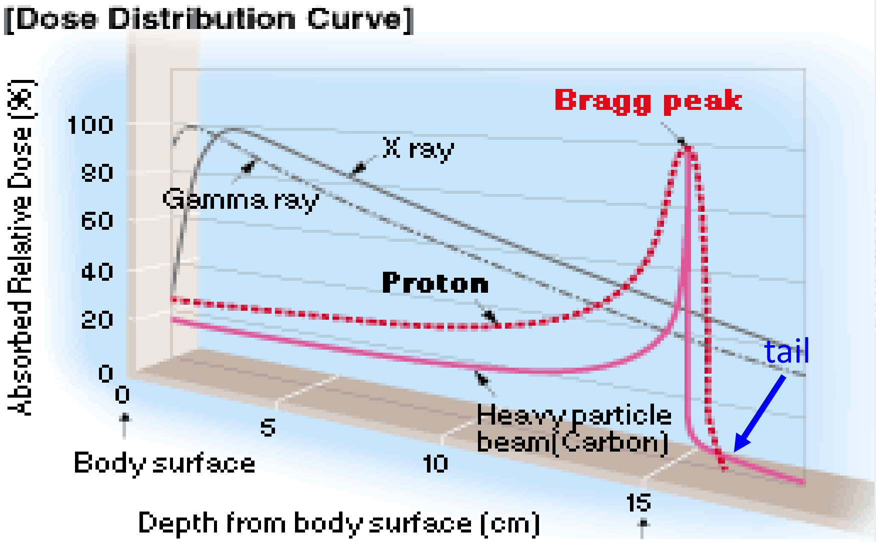
TULIP is a gantry-mounted proton therapy linac (more details in a moment) which means linac length is extremely important, and where increased gradient could decrease cost.

More generally what we are doing is transferring high-gradient technology developed for relativistic electron acceleration to low β heavy particle acceleration. But via a specific application.

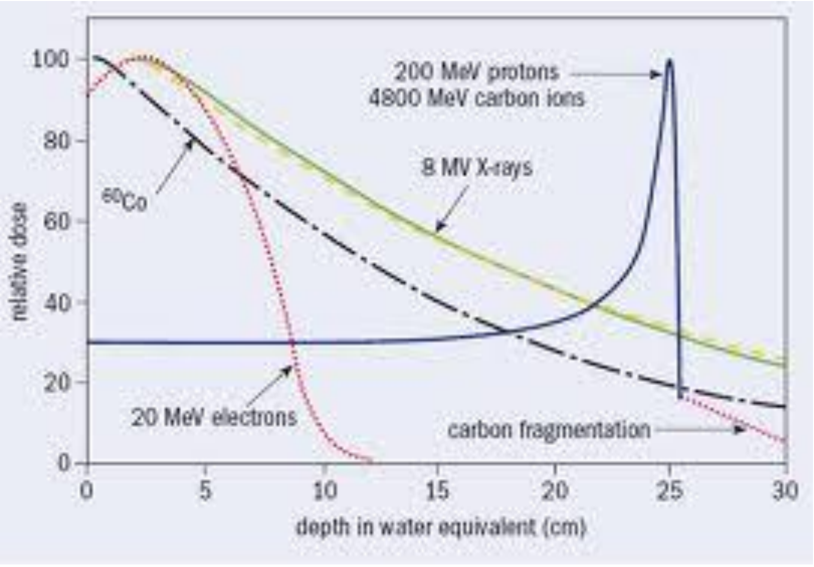
In parallel we are testing our high-gradient ideas in a parameter space far from that where they were developed. What we learn may in turn feed back to improved performance for electrons.

Basics on Hadrontherapy:

Characteristics of a therapeutical beam

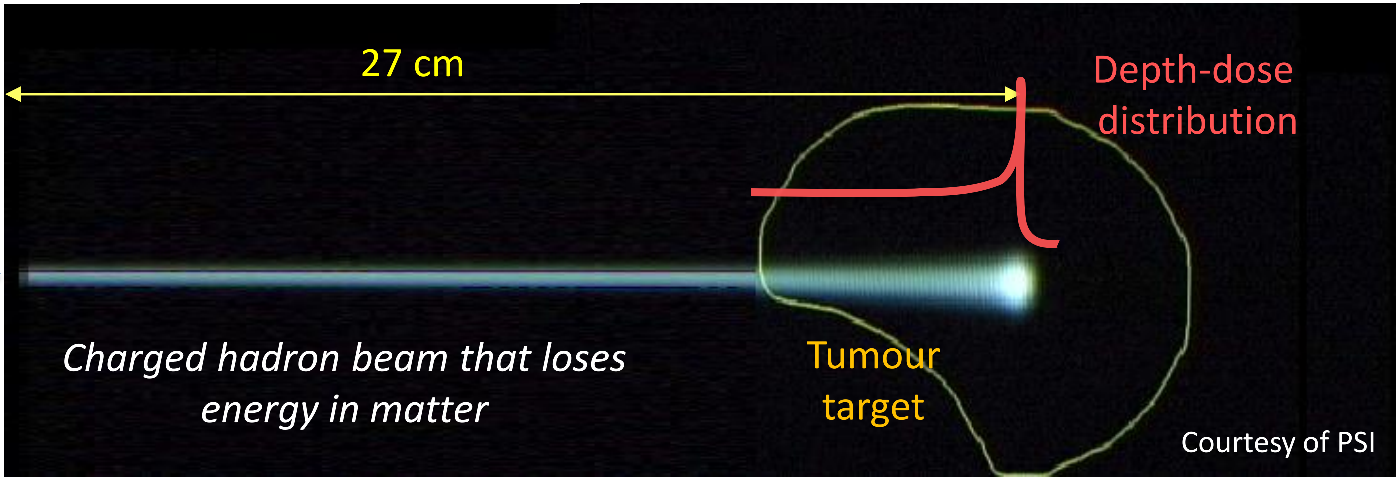


http://global.mitsubishielectric.com/bu/particlebeam/index_b.html



200 MeV - 1 nA
protons

4800 MeV – 0.1 nA
carbon ions
(radioresistant tumours)



Synchrotron-based proton therapy at CNAO in Pavia

Basics on Hadrontherapy:

Treating moving organs requires…

- **Fast Active Energy Modulation**

  (a couple of ms)

  ⇩

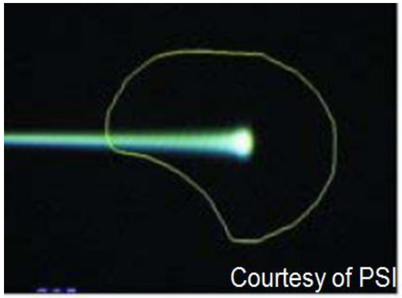
  Fast 3D correction of
  beam spot position in depth

- **Fast Cycling machine**

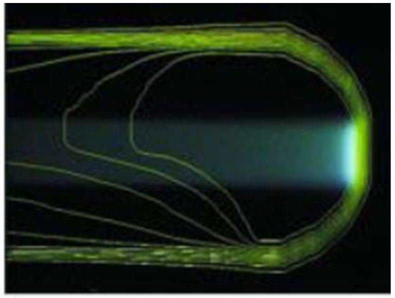
  (high repetition rate ~ 200-300 Hz)

  ⇩

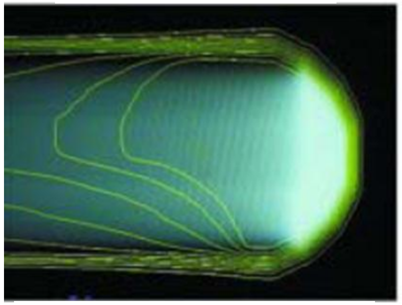
  Tumour
  MULTIPAINTING



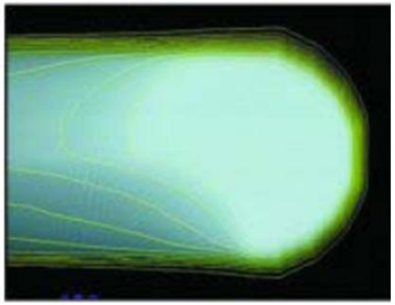
Single 'spot' pencil beam



Lateral scanning with magnets: 2 ms/step

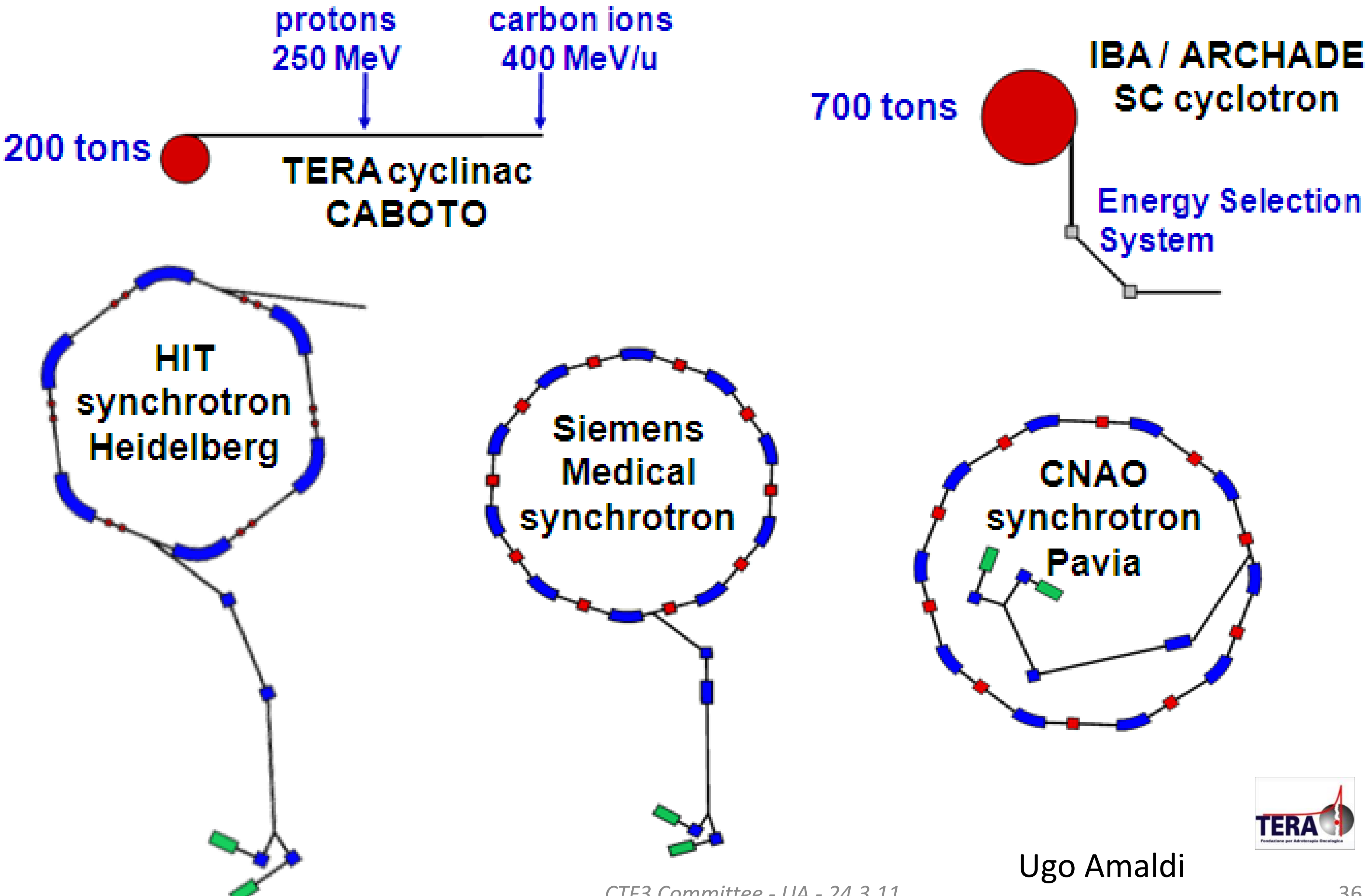


Depth scanning: ACTIVE ENERGY MODULATION



3D conformal treatment

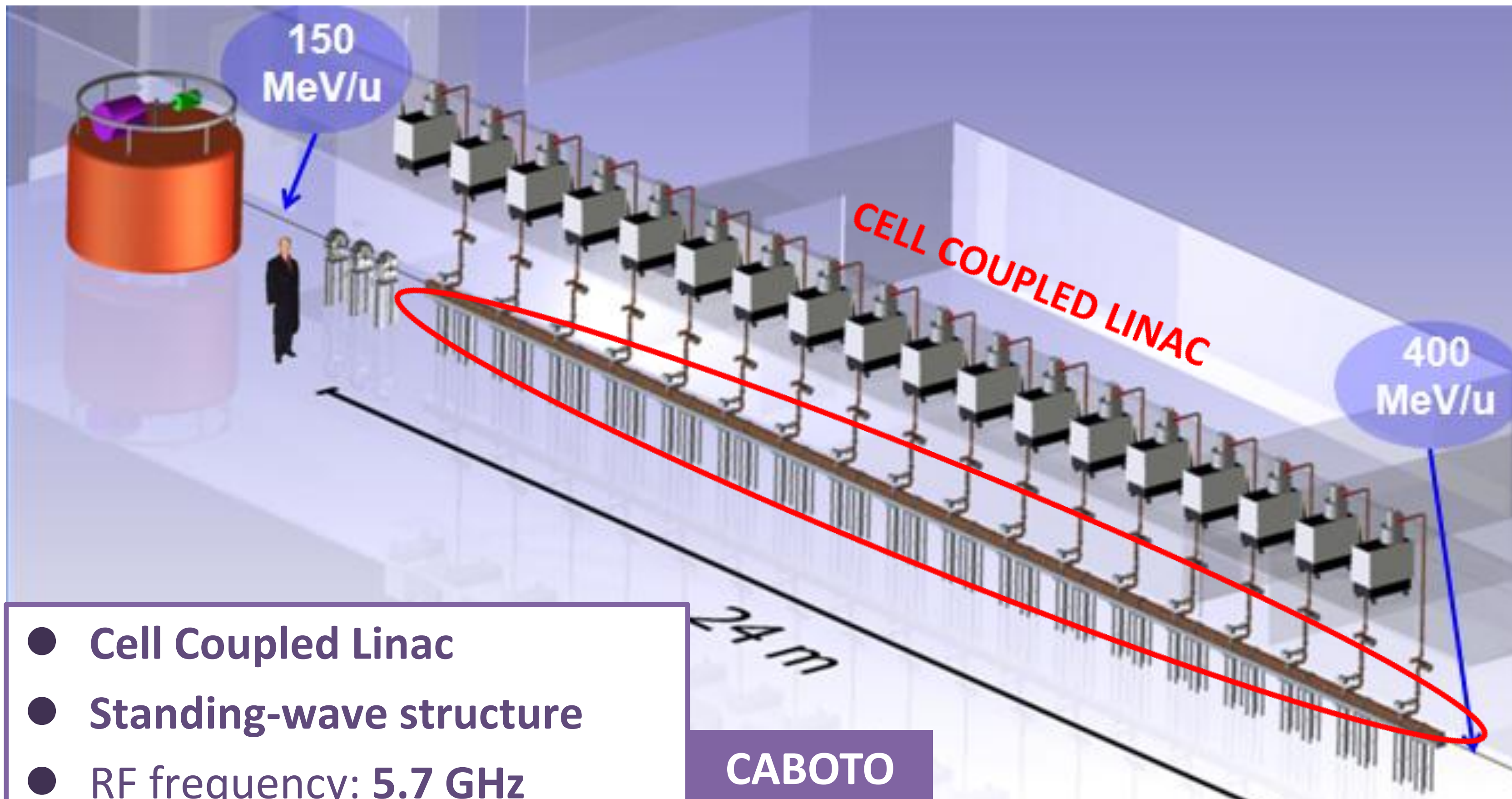
Dimensional comparison among carbon ion accelerators



Ugo Amaldi

Accelerators for Hadrontherapy

The cyclinac: cyclotron + high frequency linac



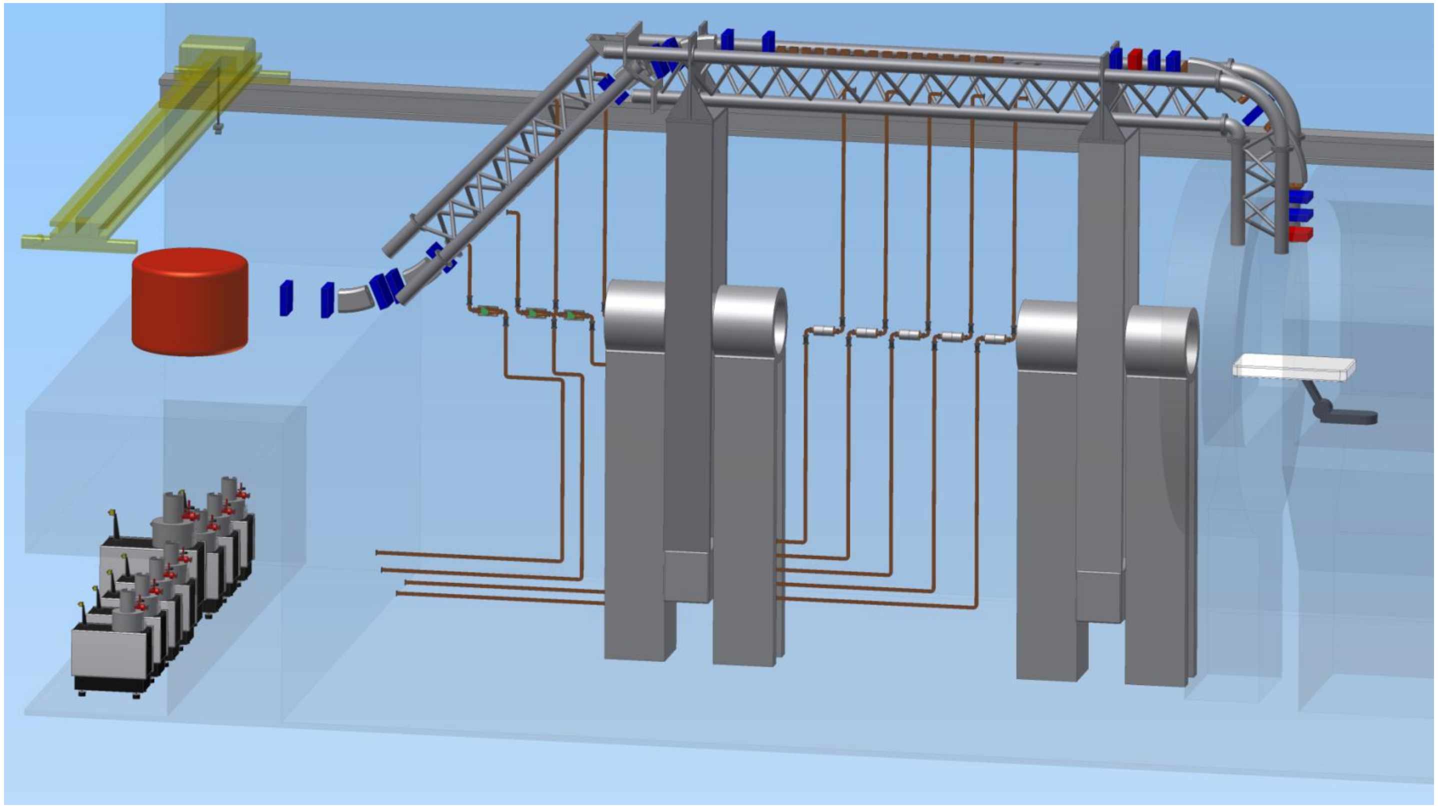
- **Cell Coupled Linac**
- **Standing-wave structure**
- RF frequency: **5.7 GHz**
- **2.5 μs**-long pulse at **300 Hz**

CABOTO

(CArbon BOoster for Therapy in Oncology)

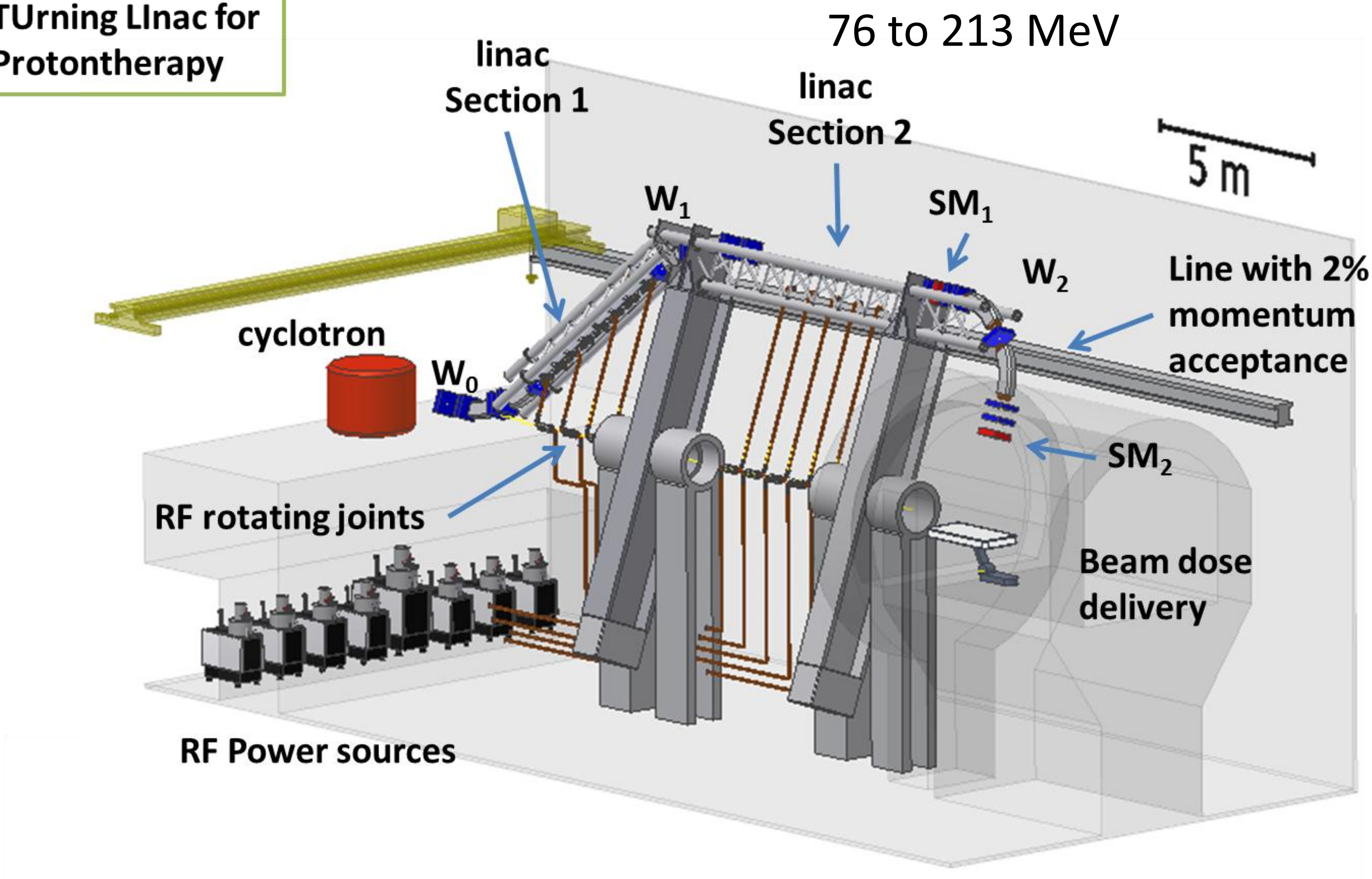
Target project - TULIP

- Proposal from the TERA Fondation lead by Ugo Amaldi
- Proton therapy single room facility
- Compact machine (accelerator and gantry together)
- Cyclinac concept with fast actively energy modulated beam



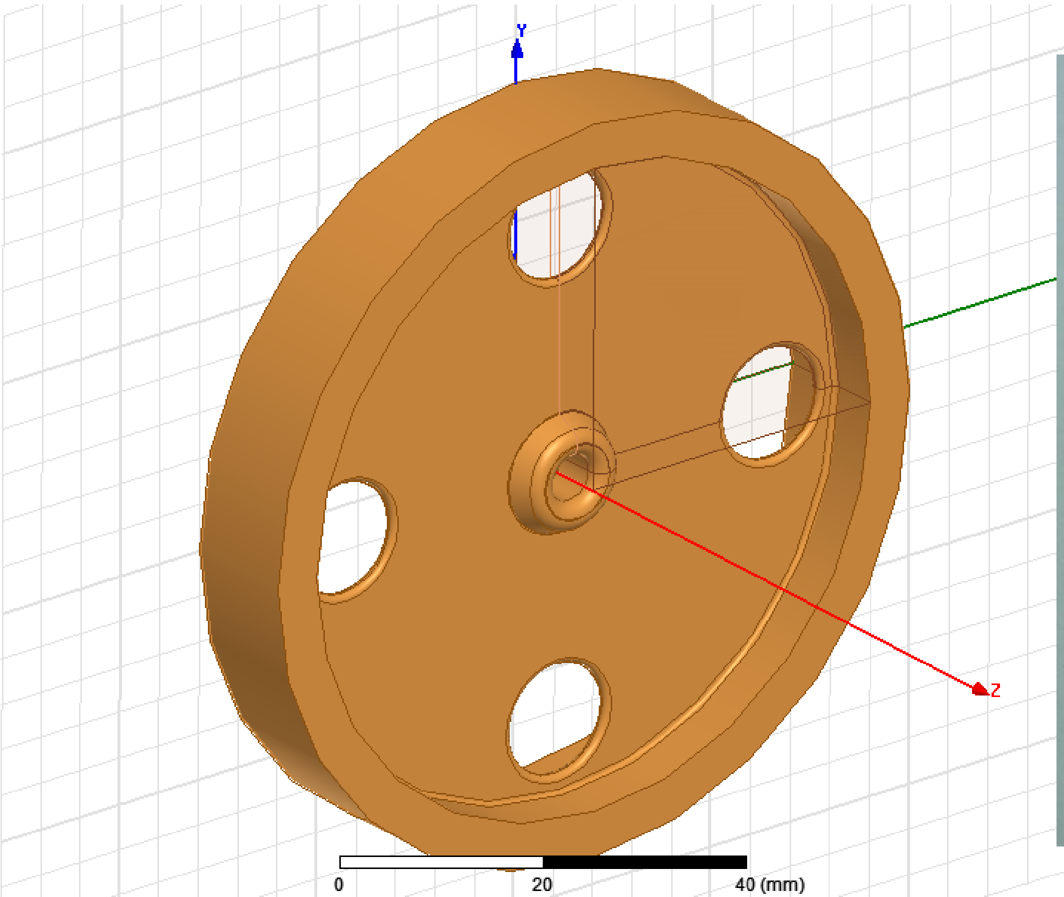
More detail

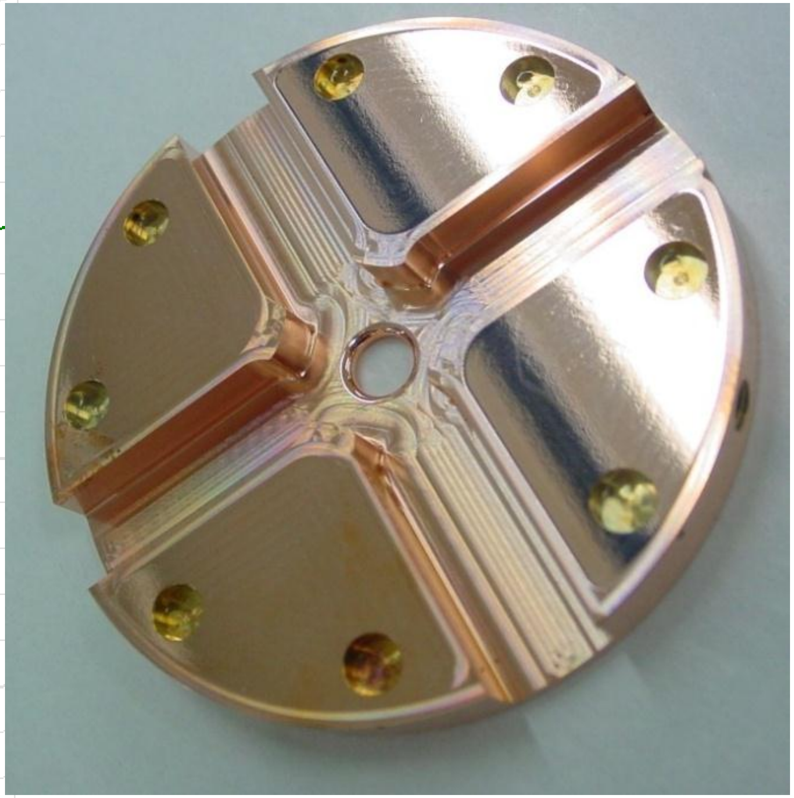
TULIP =
TUrning LInac for Protontherapy



We plan to improve it with a novel high-gradient backward wave structure based closely on the successful CLIC geometry and technology:

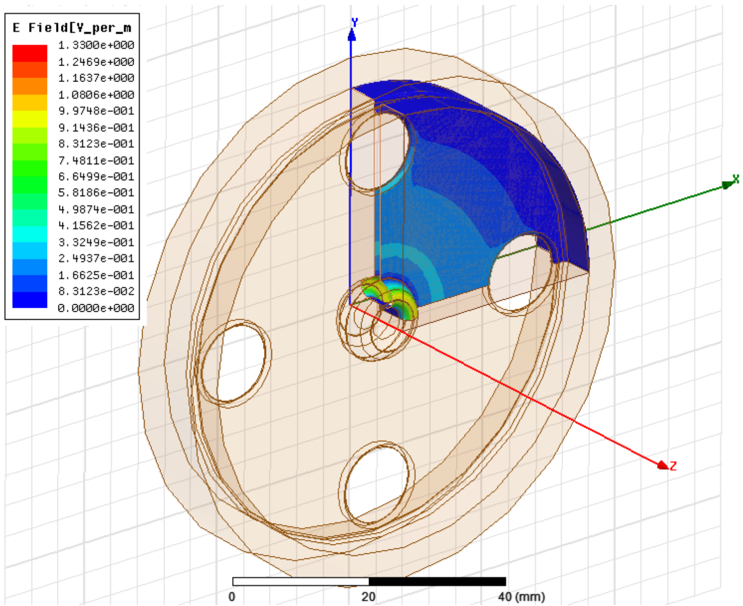
The current design of the basic cell geometry for low velocity acceleration
(still under optimization)



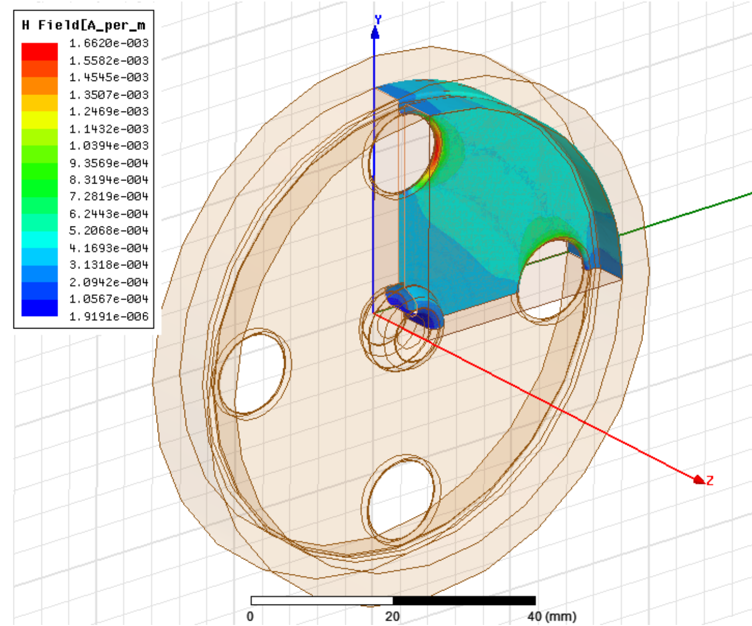


And a micron-precision CLIC cell

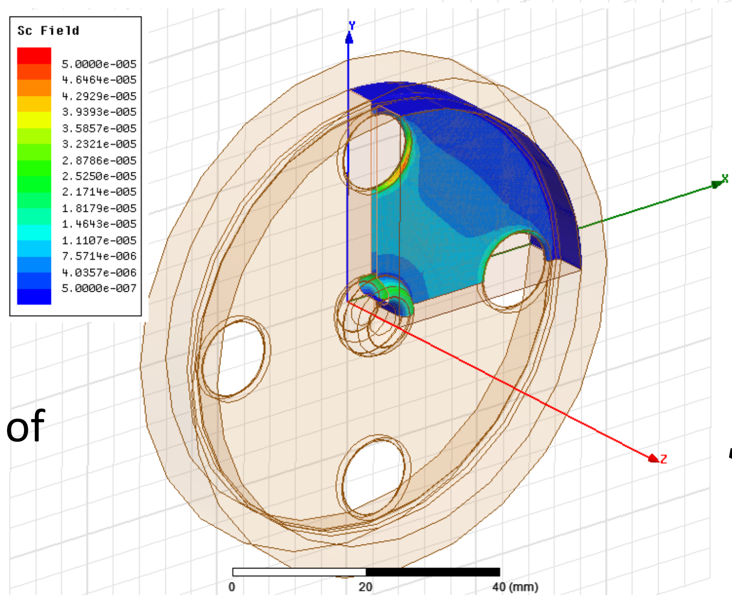
For rf enthusiasts – here you can see how we design for high gradient



Surface electric field



Surface magnetic field



Modified Poynting vector

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

Our current understanding of high-gradient limits

Special IEEE event

- Covers the relationship between linear collider studies and industry. Program: https://indico.cern.ch/getFile.py/access?contribId=0&resId=0&materialId=1&confId=200468