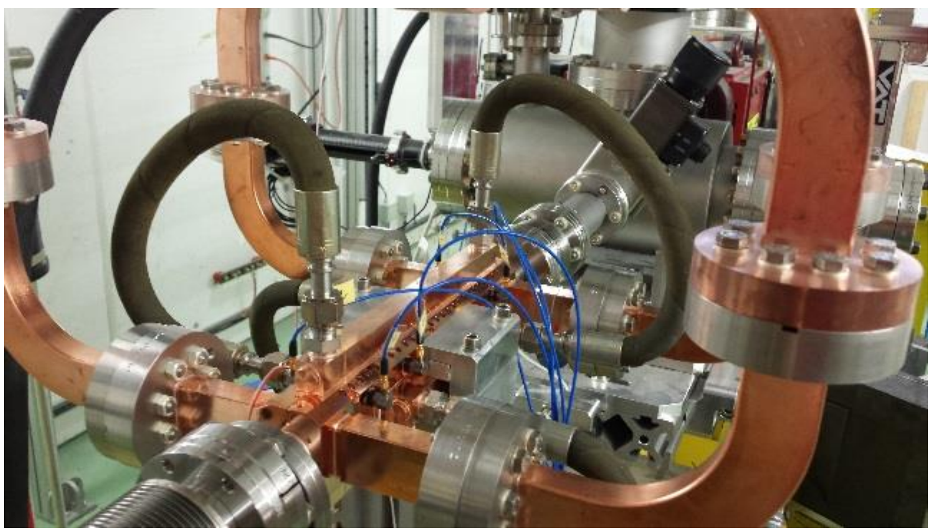
High-Gradient RF Development and Applications

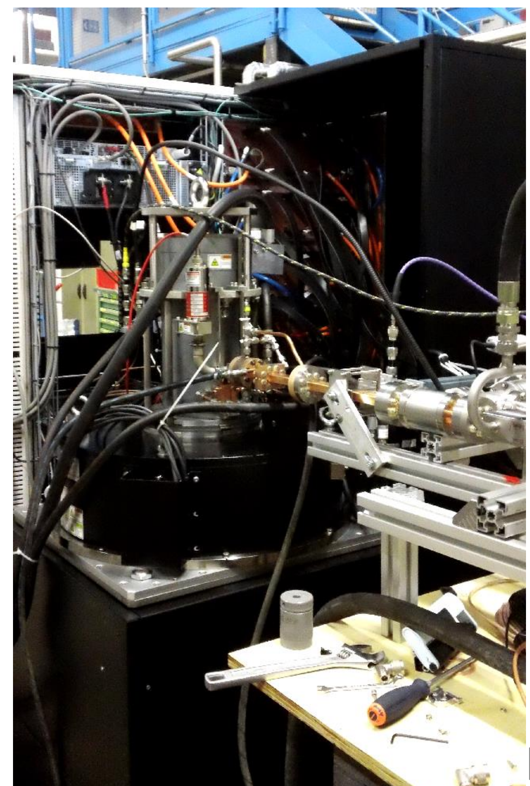
LAL, 26 November 2015

Walter Wuensch, CERN

Introduction

The CLIC collaboration has made significant progress in pushing the gradient which can achieved in normal conducting accelerating structures. In parallel it has stimulated an expansion in high-power X-band hardware and technology.





Introduction

These developments are of course crucial for CLIC's mandate to develop a TeV electron-positron collider but they are also potential very important for a wide range of other applications.

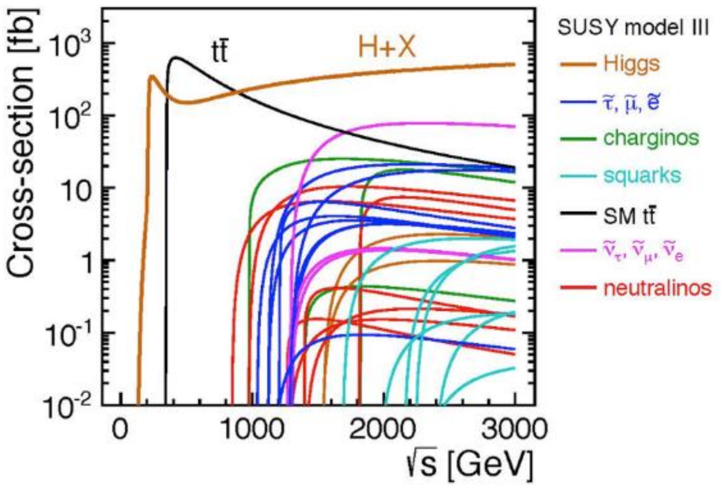
High-gradient development has also involved a fundamental study of gradient limitations, which has led to a greatly increased understanding of the dynamics of metal surfaces under high fields.

This morning I will describe the rf and fundamental high-gradient developments and give and overview of potential applications.

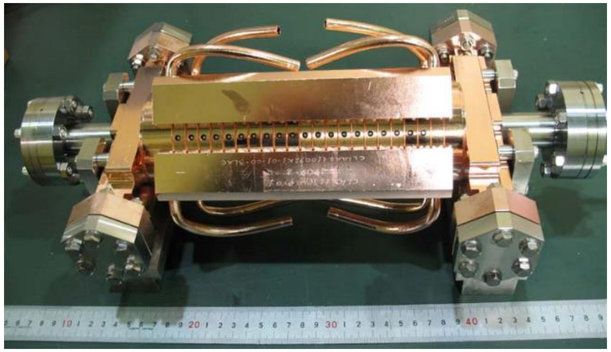
The CLIC Project

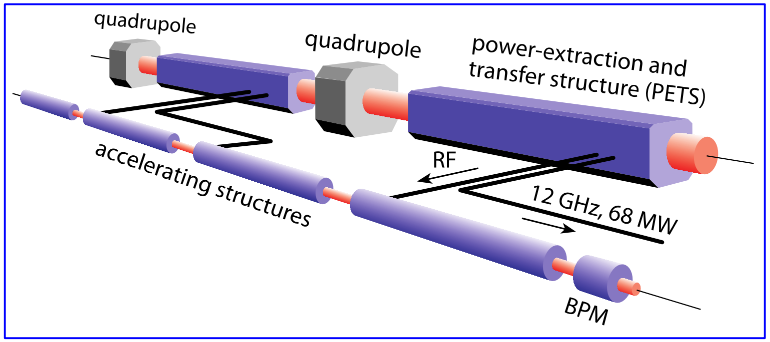
Introduction to CLIC

CLIC is an international collaboration based at CERN dedicated to developing the technology for an **e^+e^- linear collider** for the range of **250 GeV to 3 TeV.**



It is based on high-gradient, **100 MV/m,** normal conducting rf, low emittance beams and a two-beam power generation scheme. A klystron-based initial energy stage is also being considered.

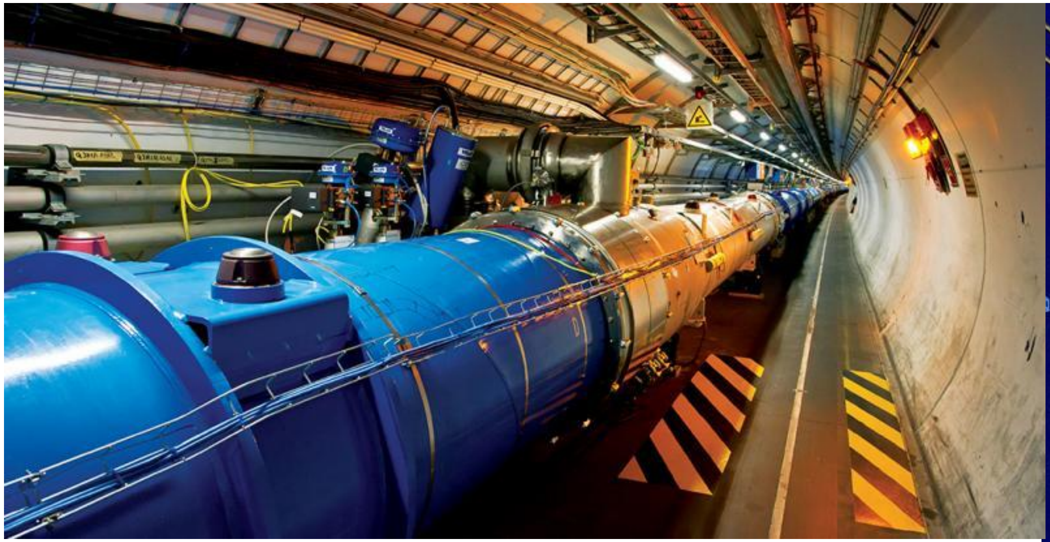


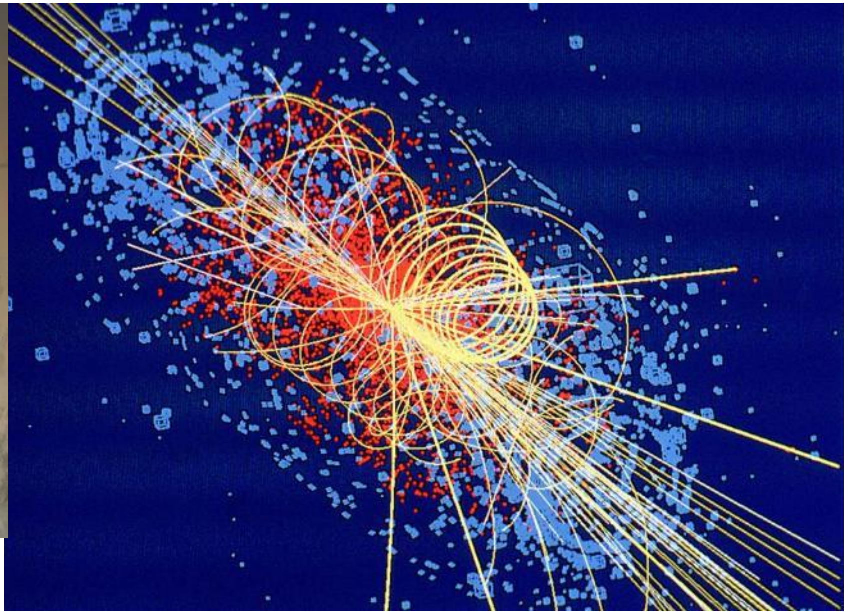


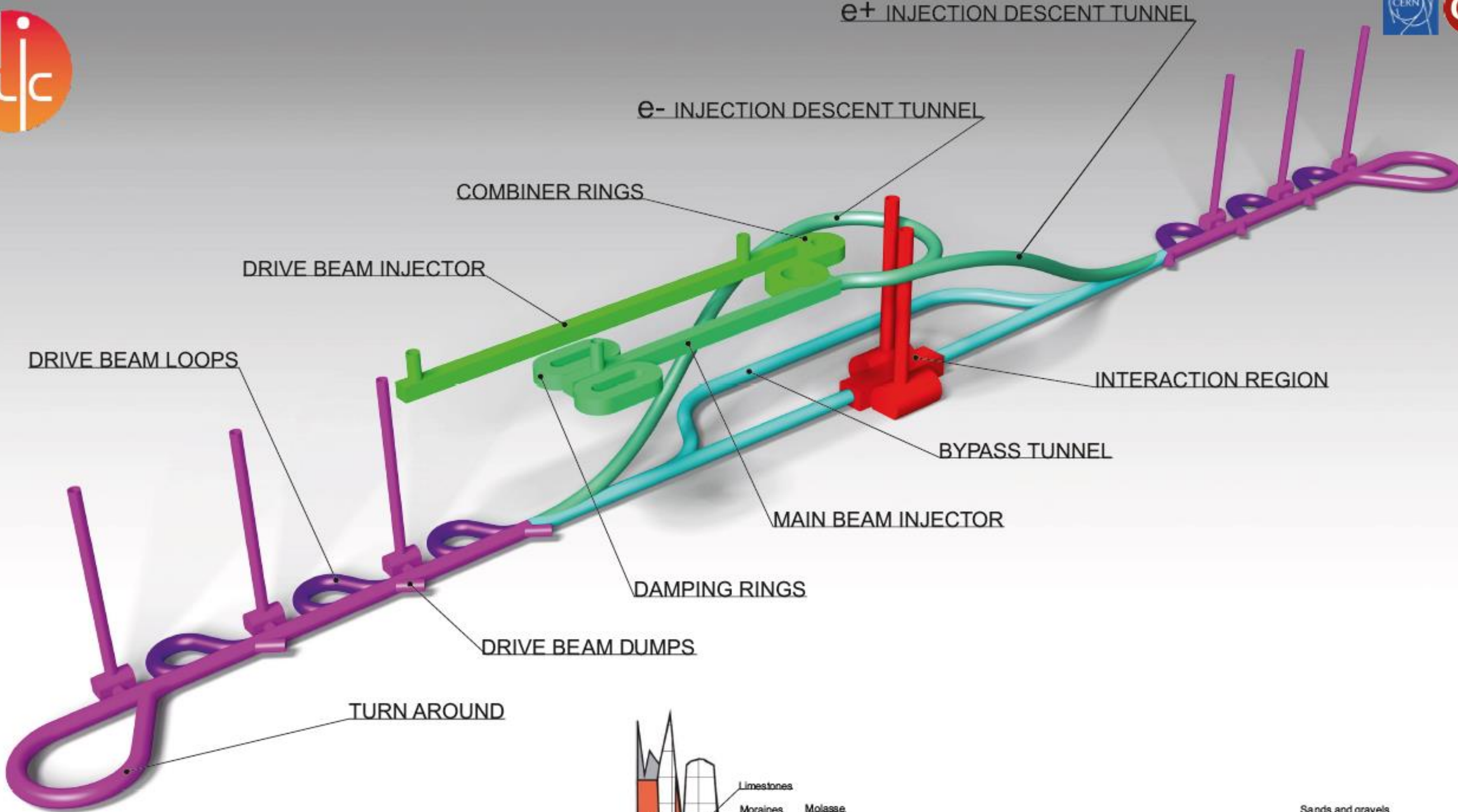
The big question

The crucial background for the CLIC study is LHC run 2. The LHC is running at nearly full energy, 13.5 TeV compared to 7 TeV in the first run.

The physics landscape in this energy range should emerge in the next two years or so. The nature of new discoveries, or their absence, will have a tremendous impact on future high energy physics studies.

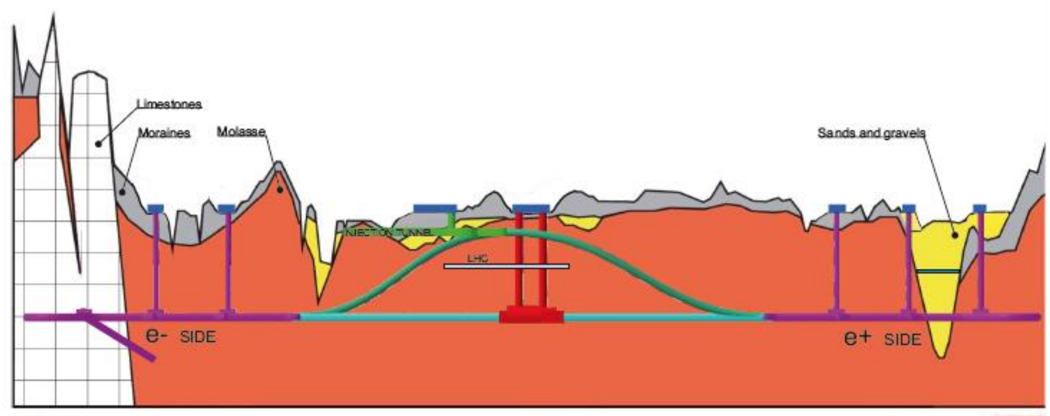




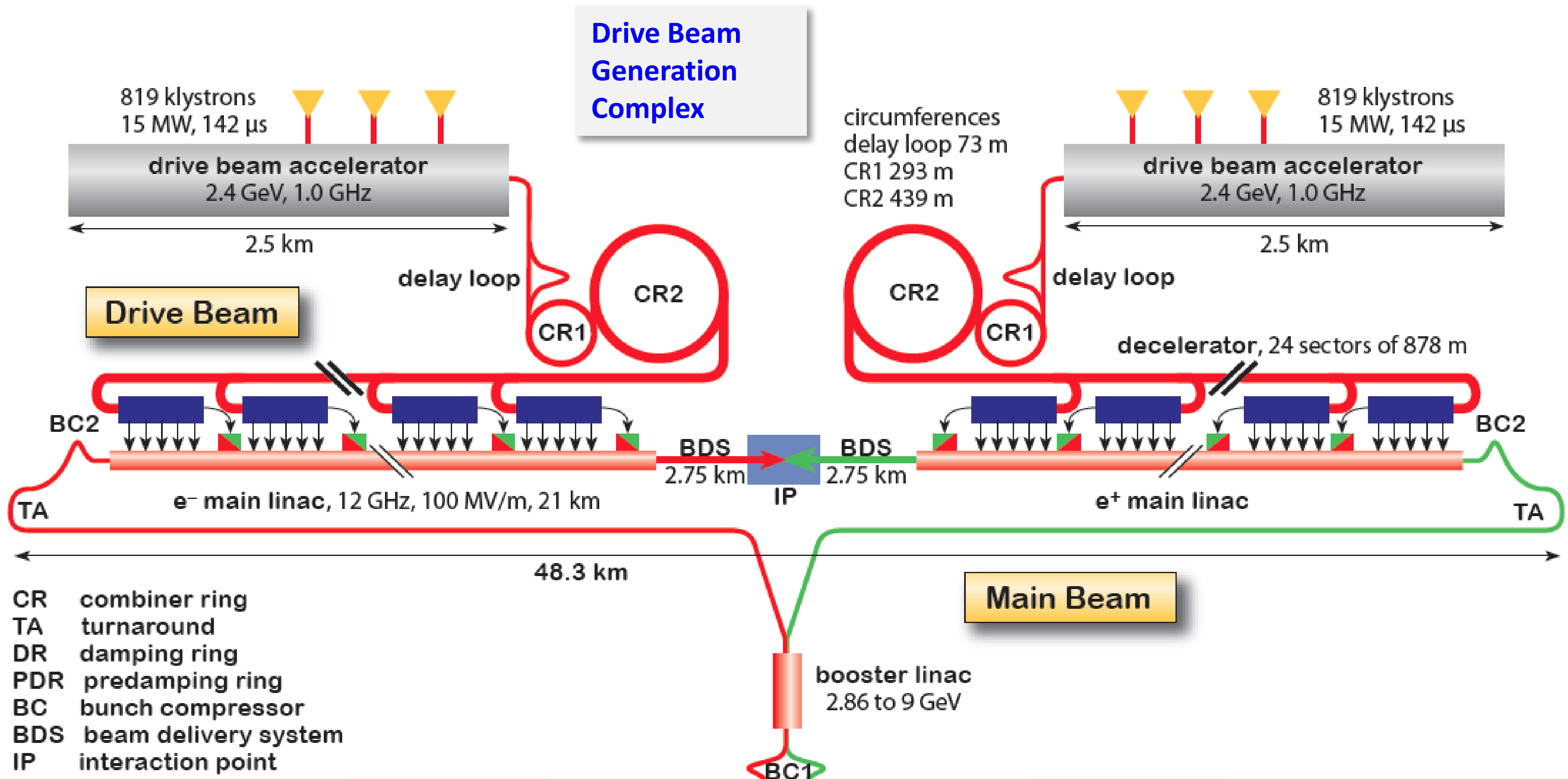


CLIC SCHEMATIC

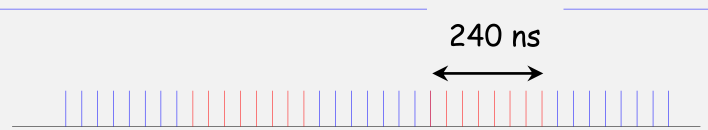
(not to scale)



CLIC Layout at 3 TeV

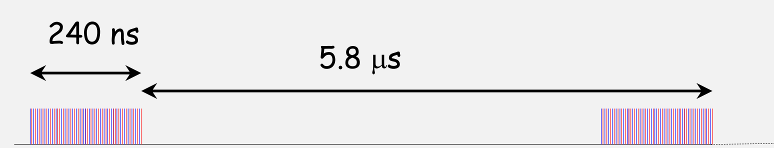


Drive beam time structure - initial



140 µs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final



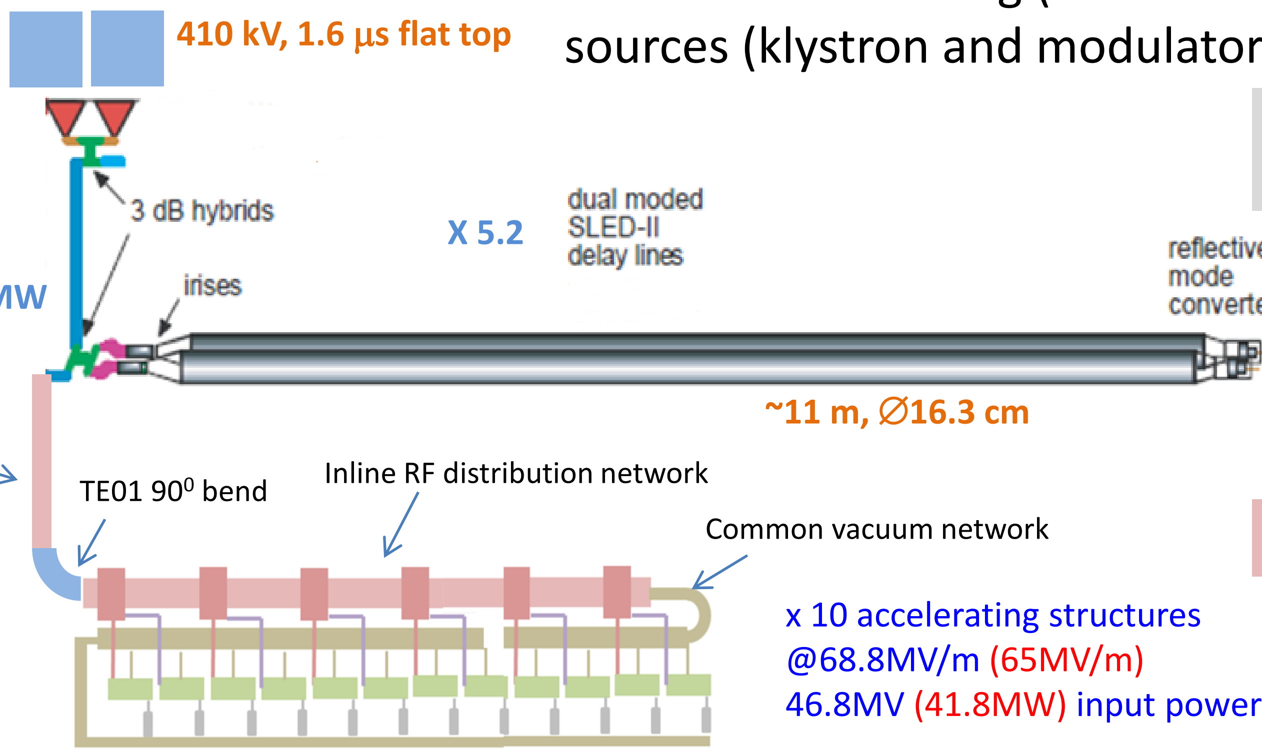
24 pulses – 101 A – 2.5 cm between bunches

Electron Linac RF Unit Layout

XbFEL

based on the existing (industrialized) RF sources (klystron and modulator)

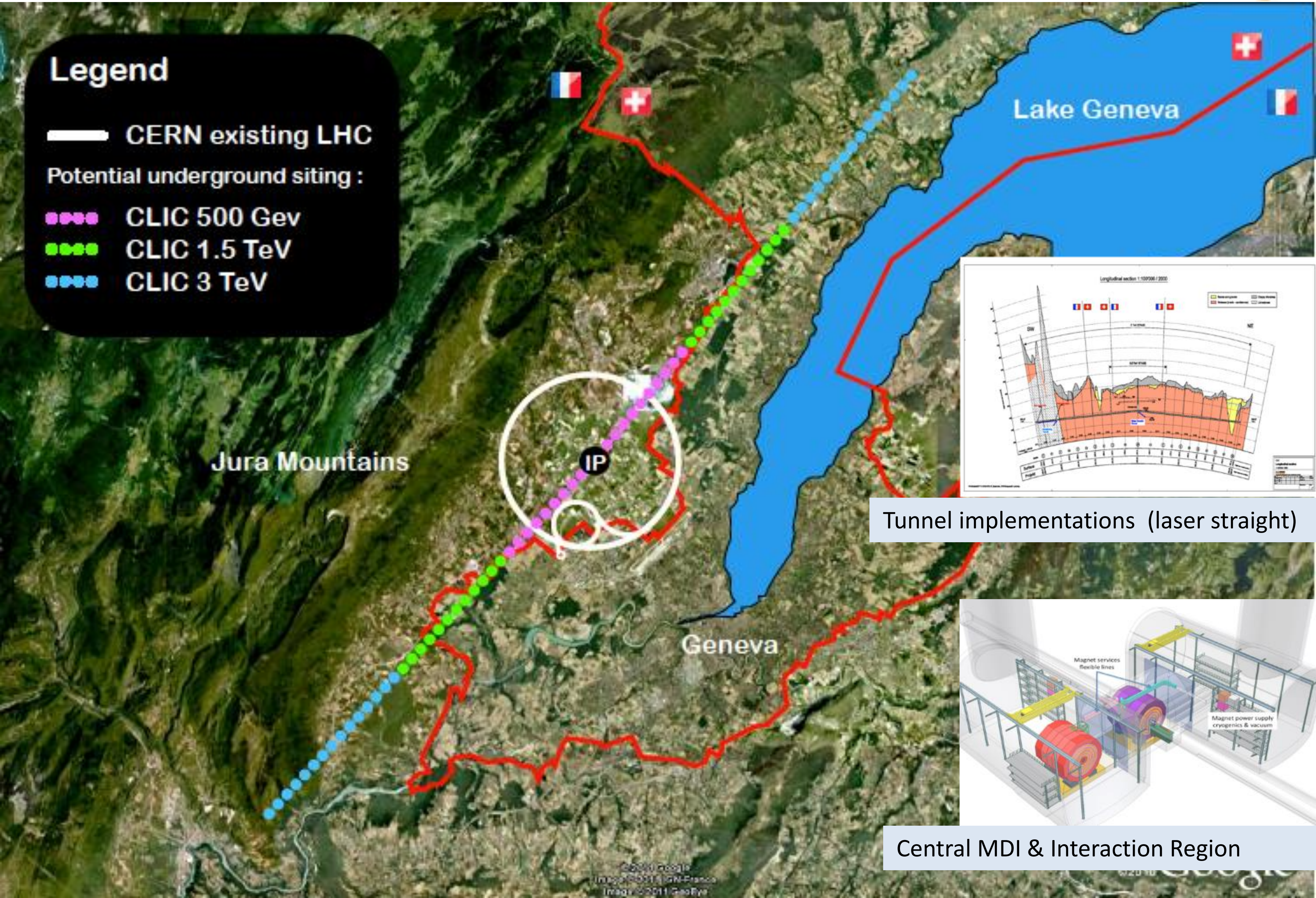
I. Syratchev, modified by me



Preliminary

This unit should provide ~488 MeV acceleration beam loading.
Need 12 RF units.
Cost 51.7 a.u., 4% more than optimum

CLIC near CERN



Tunnel implementations (laser straight)

Central MDI & Interaction Region

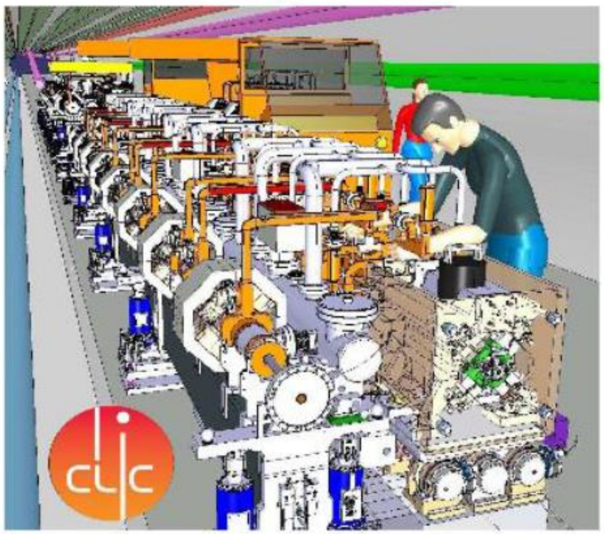
CLIC Collaboration

Accelerator collaboration has ≈ 50 institutes and the detector collaboration ≈ 25.

CDR (2012)

SLAC-R-985
KEK Report 2012-
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 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

ANL-HEP-TR-12-01
CERN–2012–003
DESY 12-008
KEK Report 2011-7
14 February 2012

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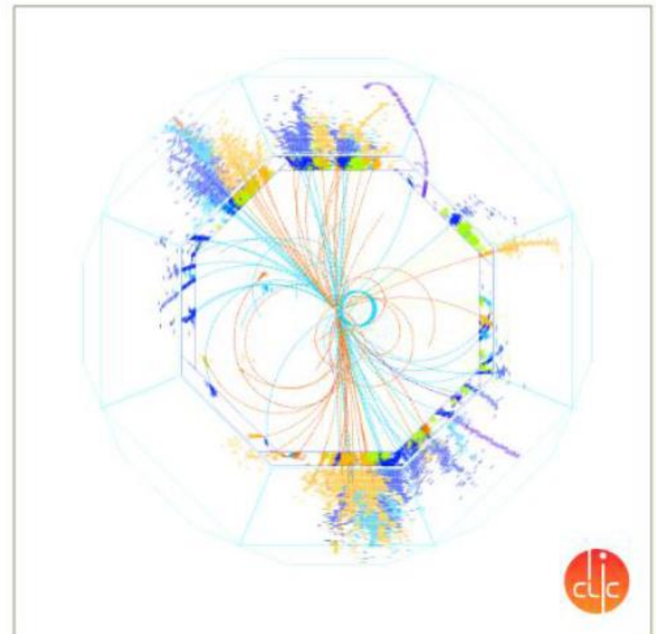


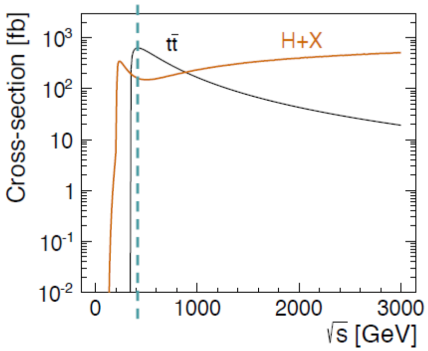
PHYSICS AND DETECTORS AT CLIC

CLIC CONCEPTUAL DESIGN REPORT

CLIC Physics Landscape

CLIC is foreseen as a staged machine:

- ★ **First stage focuses on precision SM physics**
  - **~350-375 GeV : Higgs and top**



- ★ **Not the peak of Higgs cross section**
  - **But, luminosity scales with $\sqrt{s}$**
- ★ **250 GeV and 350 GeV give similar precision for coupling measurements**
- ★ **With >350 GeV as a first stage:**
  - **provides access to top physics**

- ★ **Energies of subsequent stages motivated by physics**
  - **results from ~14 TeV LHC operation**
  - **direct dark matter searches,**

Mark Thomson CERN, January 30, 2015

CERN

CLIC re-baselining and energy staging exercise following CDR and LHC run 1.

Presentation at CLIC workshop:
http://indico.cern.ch/event/336335/overview

Conclusions

HZ production

⇨ **$\sqrt{s}$ ~ 250-450 GeV**

Top at theshold

⇨ **$\sqrt{s}$ > 350 GeV**

Recoil Mass

⇨ **$\sqrt{s}$ < 400 GeV**

Top pair production

⇨ **$\sqrt{s}$ > 360 GeV**

Top pair BSM

⇨ **$\sqrt{s}$ > 360 - ? GeV**

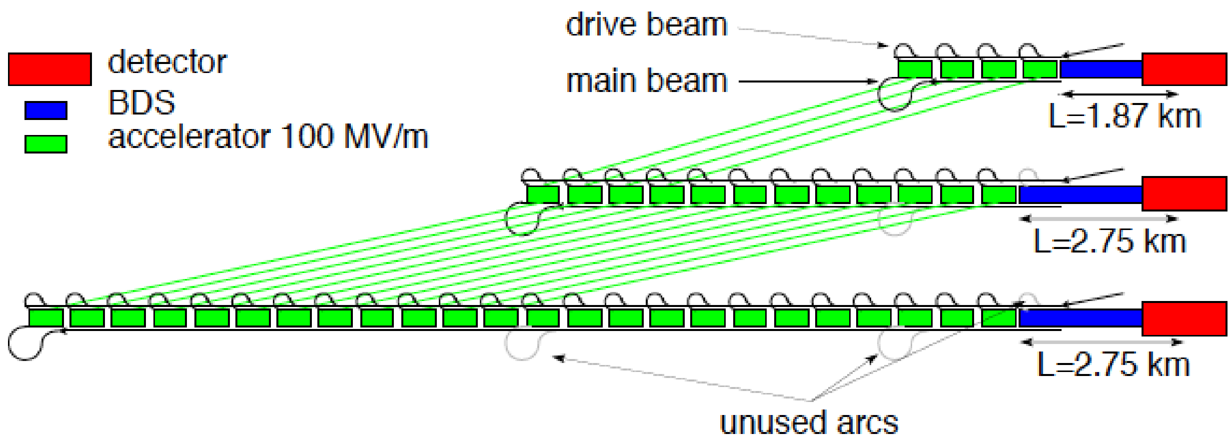
⇨ **$\sqrt{s}$ ~ 380 GeV**

Still good for HZ
Provides valid top quark program

Mark Thomson CERN, January 30, 2015 25

Staged Design

Goal: Develop a staged design for CLIC to optimise physics and funding profile, using knowledge from CDR



- First stage: E_{cms}=~~360GeV~~ 380Gev, $L=1.5x10^{34}cm^{-2}s^{-1}$, $L_{0.01}/L>0.6$
  - Luminosity has been defined based on physics and machine studies in 2014
  - 420 GeV stage has also been explored, but physics prefers 360GeV
- Second stage: E_{cms}=O(1.5TeV)
- Final stage: E_{cms}=3TeV, $L_{0.01}=2x10^{34}cm^{-2}s^{-1}$, $L_{0.01}/L>0.3$

High-Gradient and X-Band Development

LAL, 26 November 2015

Walter Wuensch, CERN

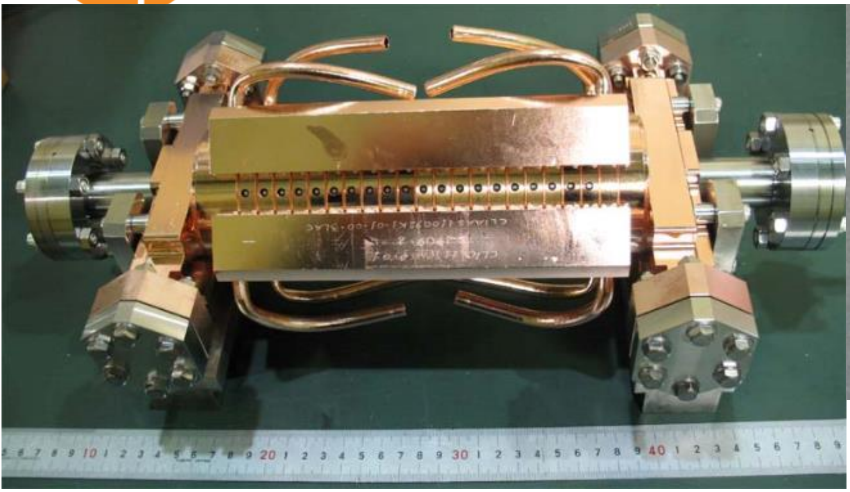
Objectives

One of the key objectives of the CLIC study has been to prove that we can achieve 100 MV/m accelerating gradient necessary for a 3 TeV center of mass collider.

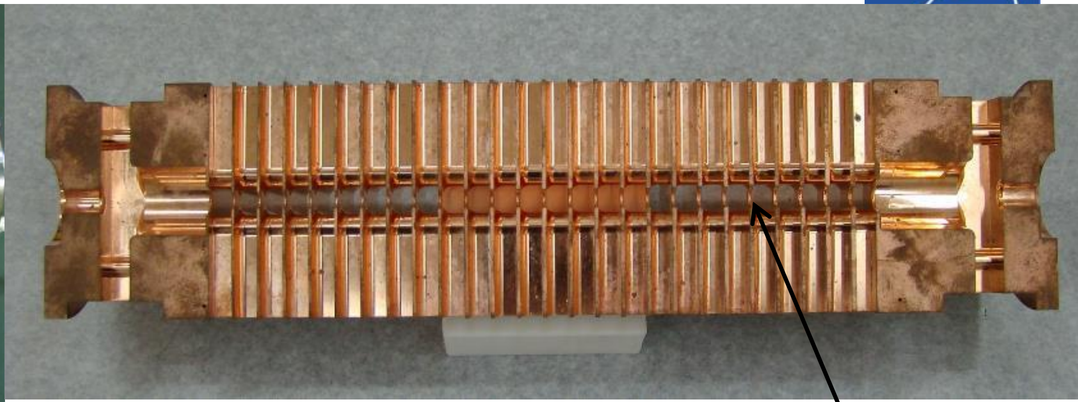
Along with this objective is the requirement that very low emittance bunch trains must be accelerated, meaning that long and short range wakefields must be controlled. This means micron-precision manufacture and assembly along with higher-order-mode suppression.

I will now describe some of these issues.

Accelerating structure



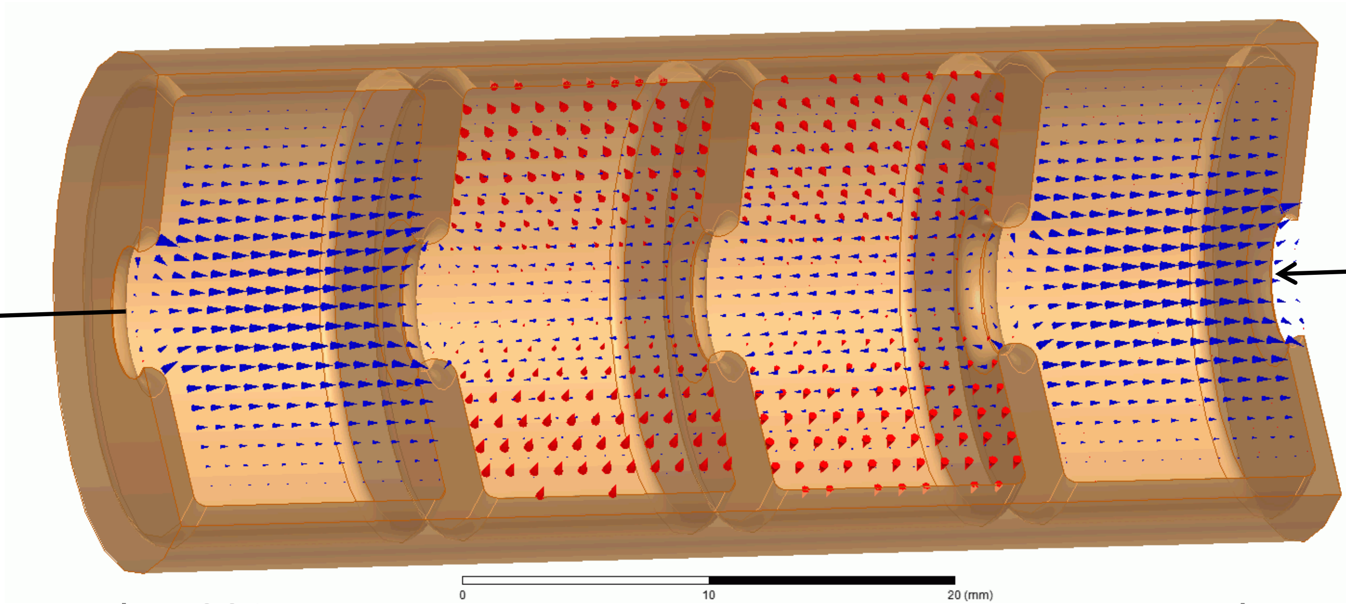
Outside



Inside

11.994 GHz X-band

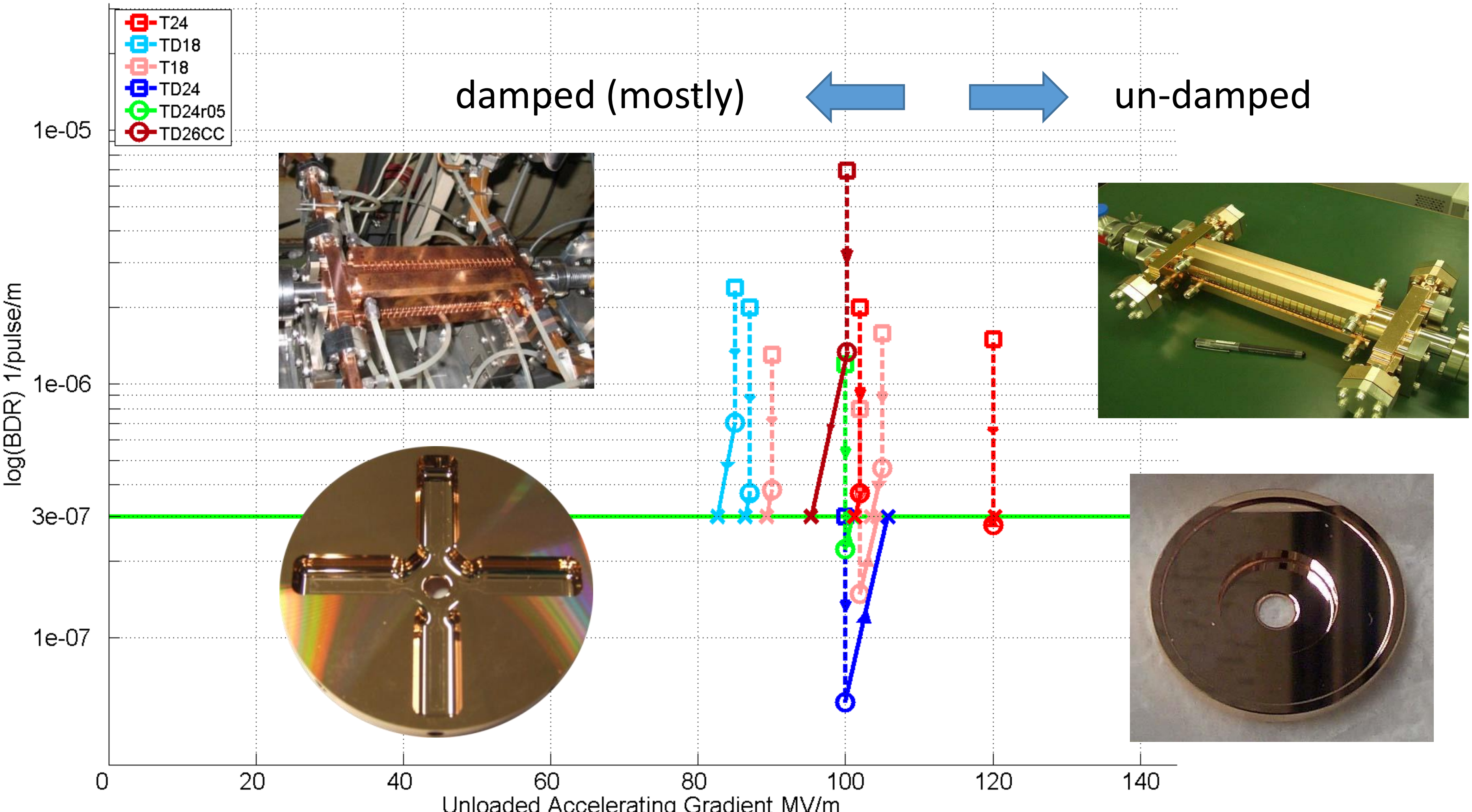
6 mm diameter
beam aperture



beam
propagation
direction

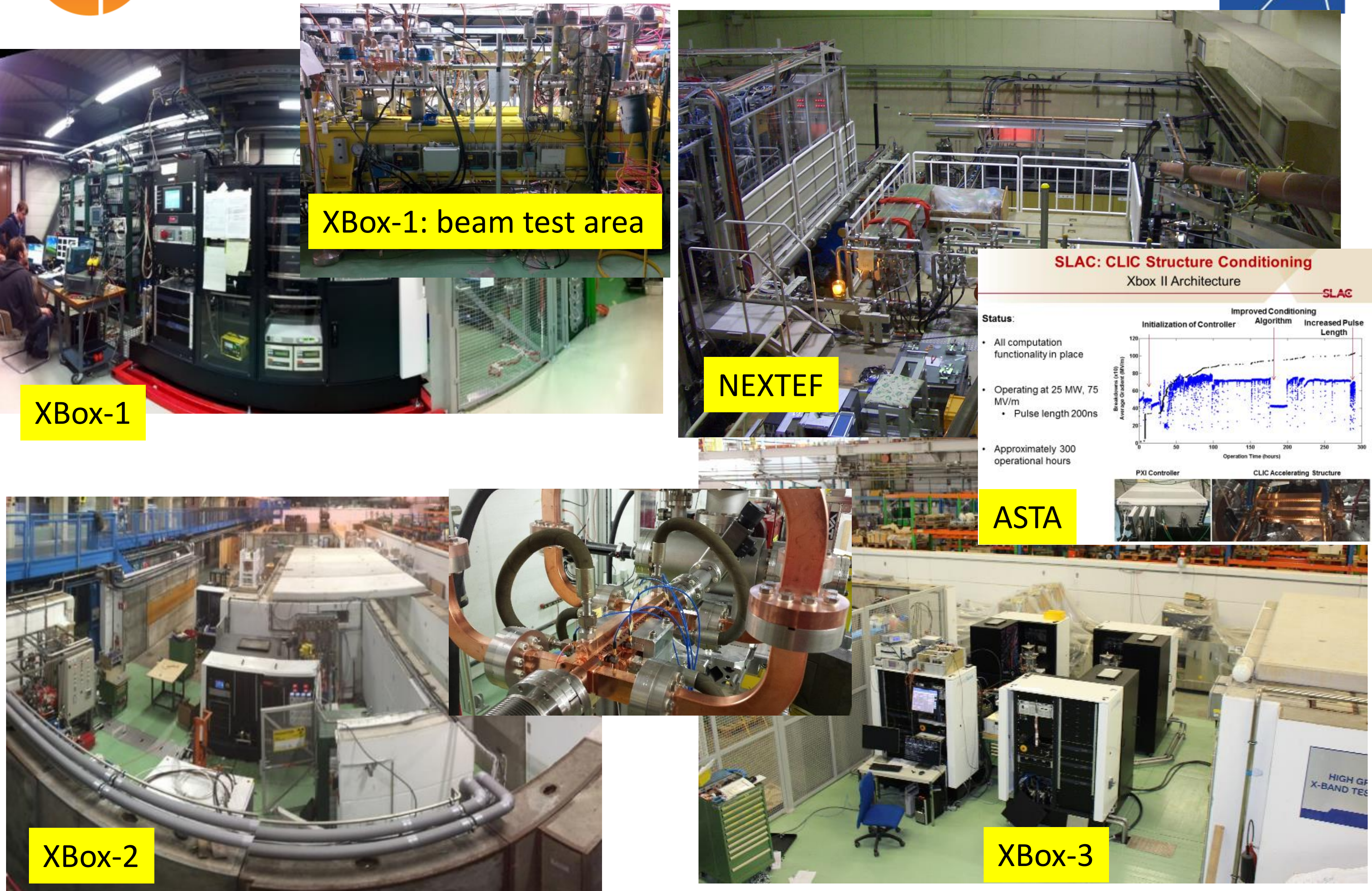
Concept

State of the gradient
Full length prototypes



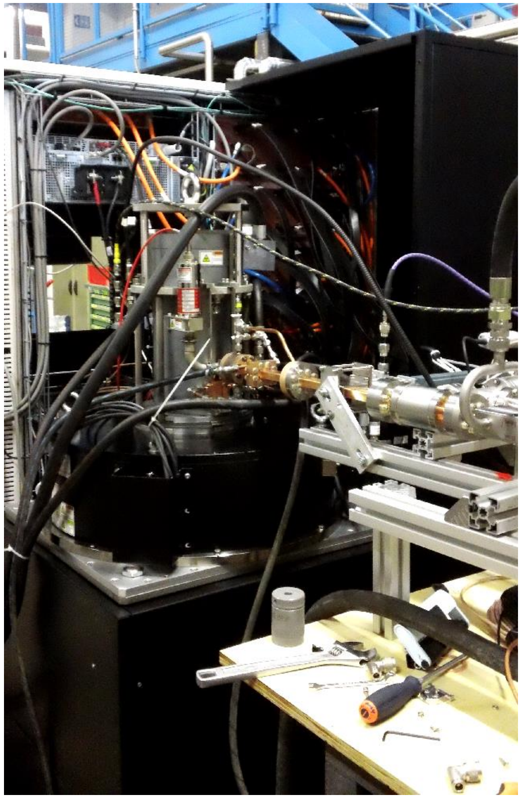
A. Degiovanni

X-band test stands around the world



Commercial X-band rf power sources

CPI 50 MW, 1.5 μs, 50 Hz

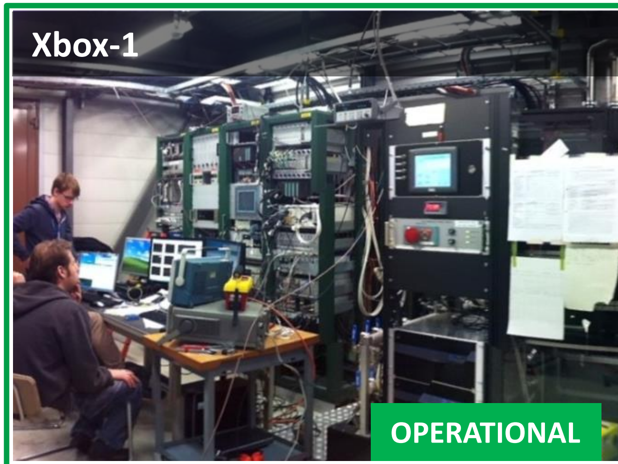


Toshiba 6 MW, 5 μs, 400 Hz

Commercial X-band klystrons at CERN. Availability of **commercial** rf power sources essential for spread and development of technology.

I. Syratchev, G. McMonagle, N. Catalan

The Xboxes



CPI 50MW 1.5us klystron
Scandinova Modulator
Rep Rate 50Hz

Current test:
Dogleg beam-loading experiment, **TD26CC#1** (in CTF3 LINAC)

Previous tests:
TD24R05 (CTF2, 2013)
TD26CC#1 (CTF2, 2013)
T24 (Dogleg, 2014-15)

CPI 50MW 1.5us klystron
Scandinova Modulator
Rep Rate 50Hz

Current test:
T24_OPEN (in halves)

Previous test:
CLIC Crab cavity (2014-15)

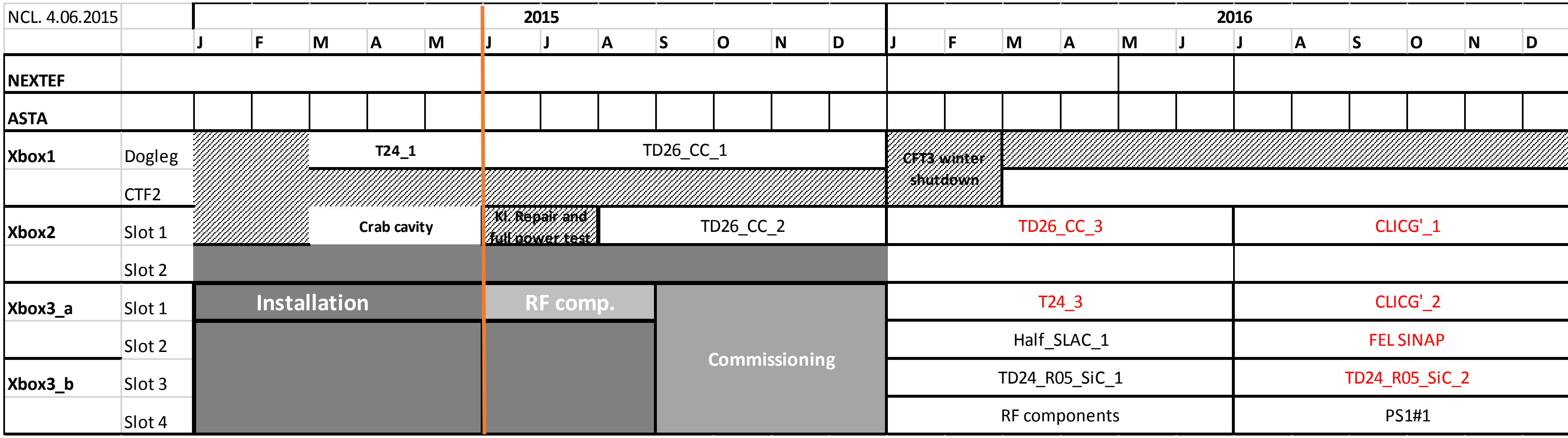
Xbox-3B/C/D: COMMISSIONING

4x Toshiba 6MW 5us klystron
4x Scandinova Modulators
Rep Rate 400Hz

LLRF, pulse compressors and waveguide network to be completed at the end 2015

Medium power test:
3D printed Ti waveguide (Xbox-3A)

Schedule



N. Catalan

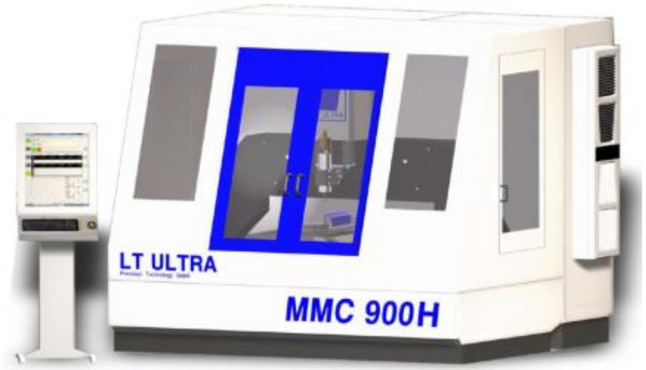
CLIC will achieve full capacity at the beginning of next year.

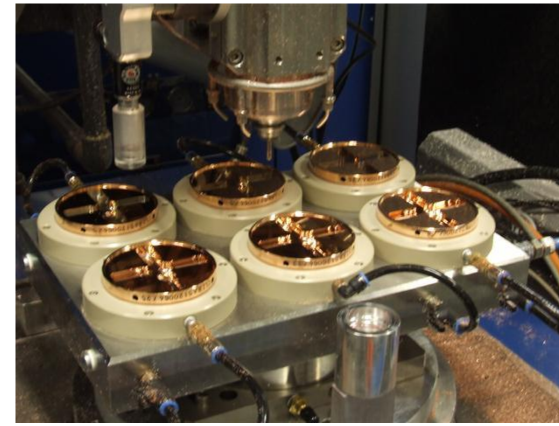
Testing capability is absolutely essential for development.

Tests take a long time due to conditioning…

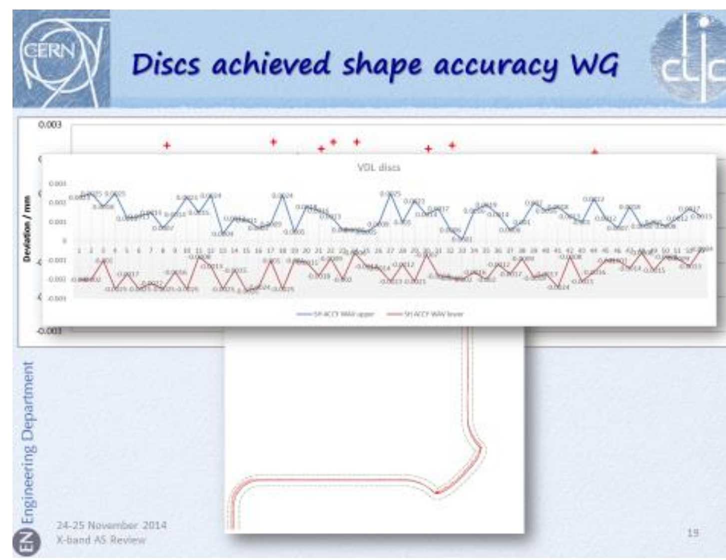
Commercial micron-precision machining

S. Atieh, A. Solodko





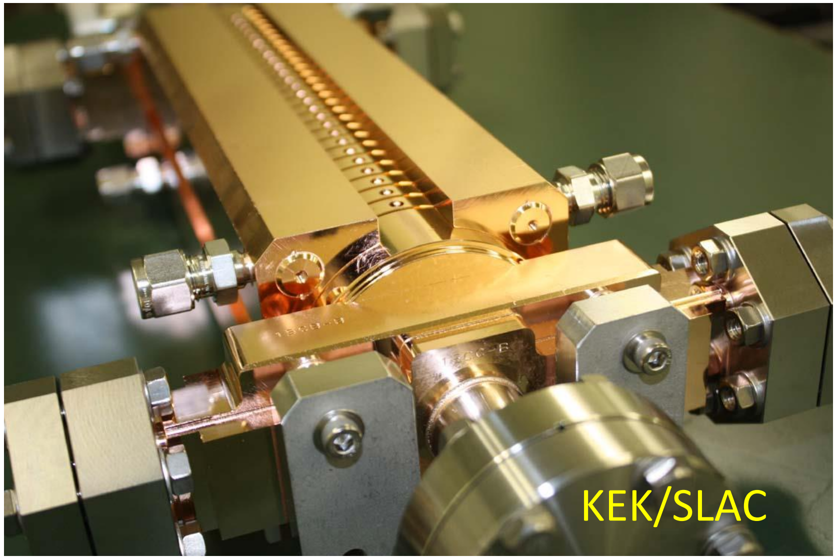
Micron-precision turning and milling.



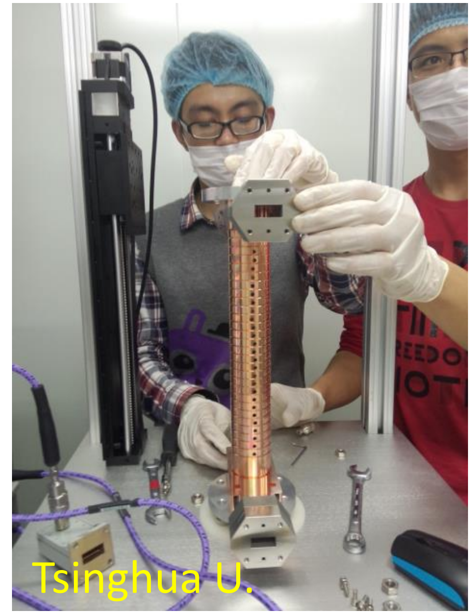
High-gradients, high-frequencies and tight mechanical tolerances go together.
There is a solid industrial supplier base capable of making the micron tolerance parts we need.
The main risk is maintaining continuity – projects and orders are sporatic.

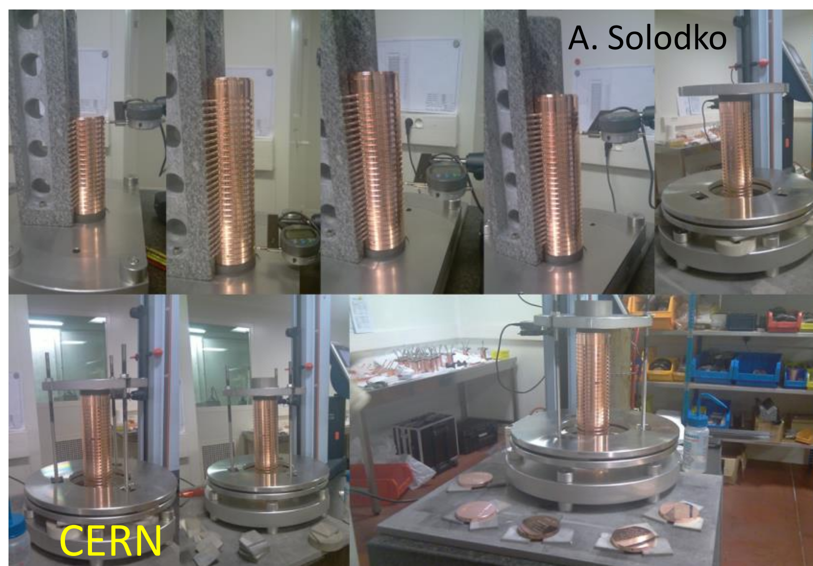
Assembly – still laboratory based

T. Higo



J. Shi





Baseline manufacturing flow

RF DESIGN

ENGINEERING DESIGN (3D models, 2D drawings)

ULTRA PRECISION MACHINING

QUALITY CONTROL AT FACTORY

NOT CONFORM

CONFORM

Add a final dimensional control

QUALITY CONTROL AT CERN

CLEANING (LIGHT ETCHING)

ASSEMBLY OF COUPLERS (brazing, machining)

PRELIMINARY RF CHECK

DIFFUSION BONDING OF DISC STACK

BRAZING OF COUPLERS, TUNING STUDS, COOLING CIRCUITS

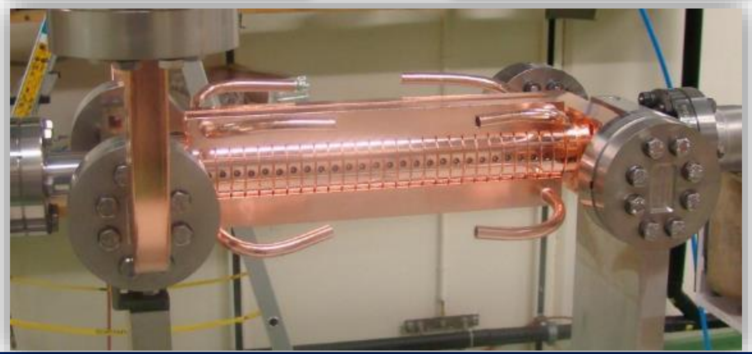
LEAK TIGHTNESS TEST

RF CHECK AND TUNING

BAKING (vacuum 650 °C, 10 days)

INSTALLATION

PACKAGING AND SHIPPING

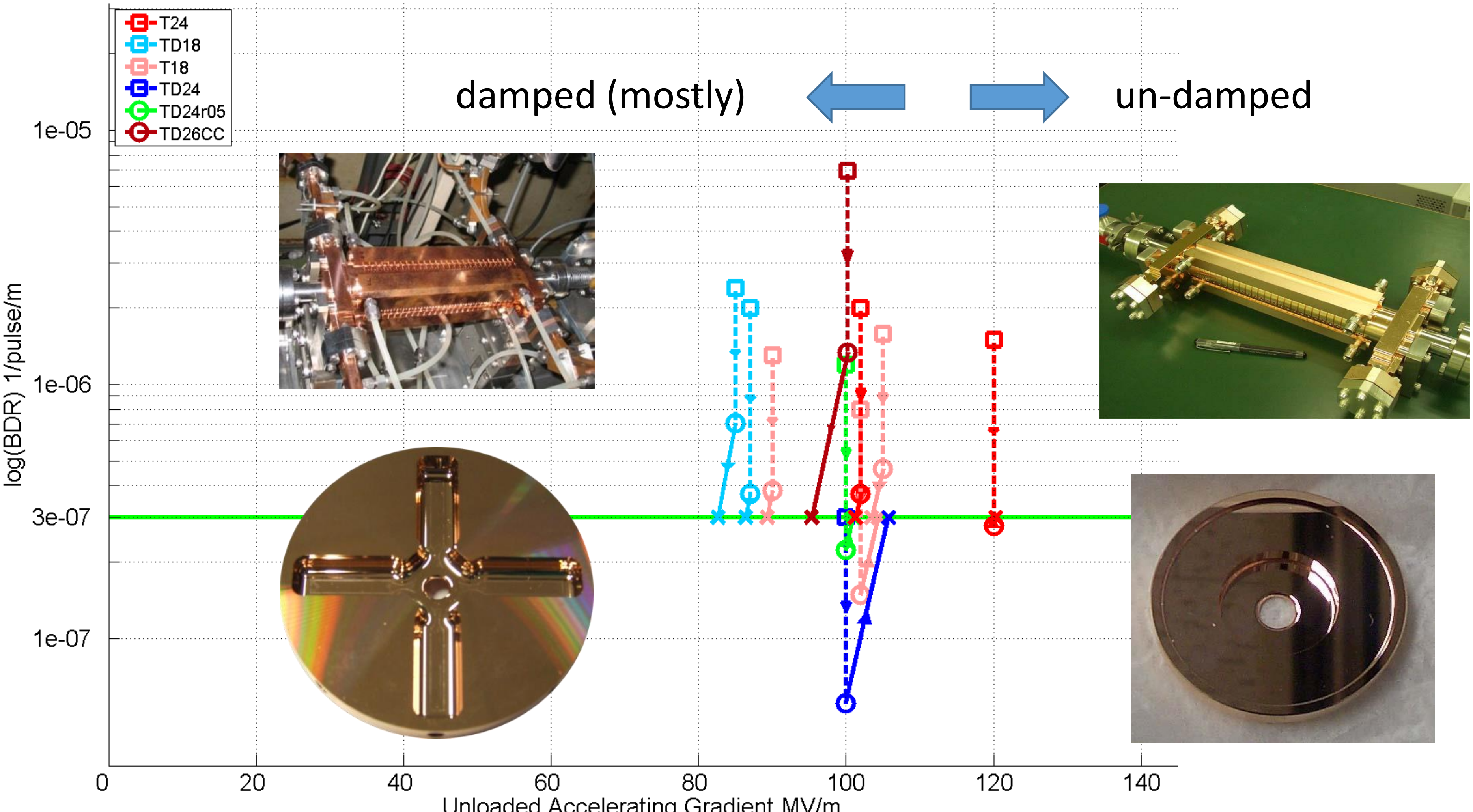


Industrialization

- Currently we order all parts in industry, especially key-technology micron-precision diamond machining, but assemble the structures at CERN (but using commercial furnaces).
- Assembly is a big fraction of the cost.
- We are preparing to go to industry for complete prototype structures.
- This requires that we have our procedure appropriately documented.
- The assembly technology – chemistry, heat treatment, etc. – was originally taken from NLC/JLC program. Excellent fundamentally but we believe contains unnecessary and poorly justified steps so we are fine tuning it. Requires feedback from testing.
- No company has 50 MW of X-band power.

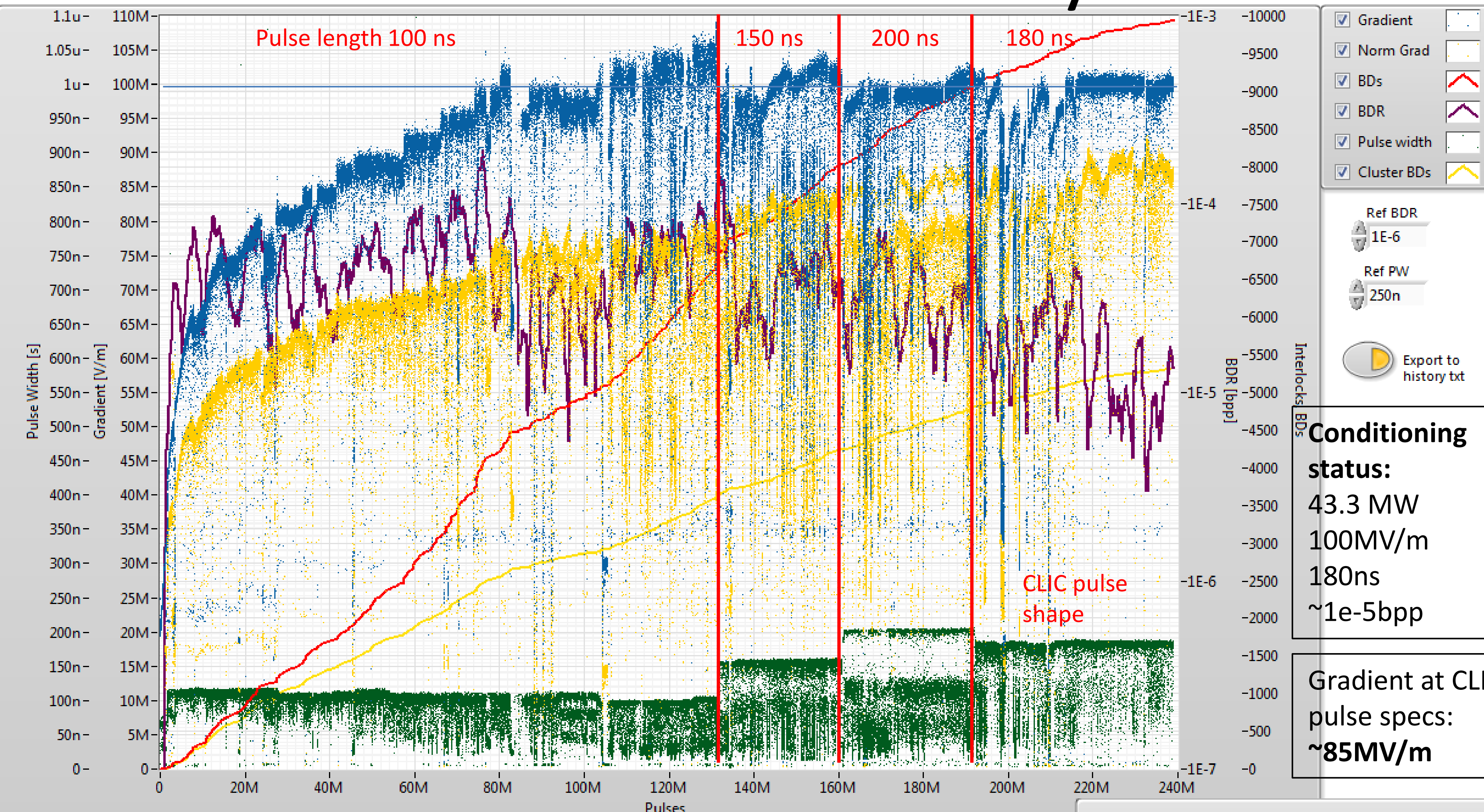
Performance

State of the gradient
Full length prototypes



A. Degiovanni

TD26CC full history



Conditioning status:
43.3 MW
100MV/m
180ns
~1e-5bpp

Gradient at CLIC pulse specs:
~85MV/m

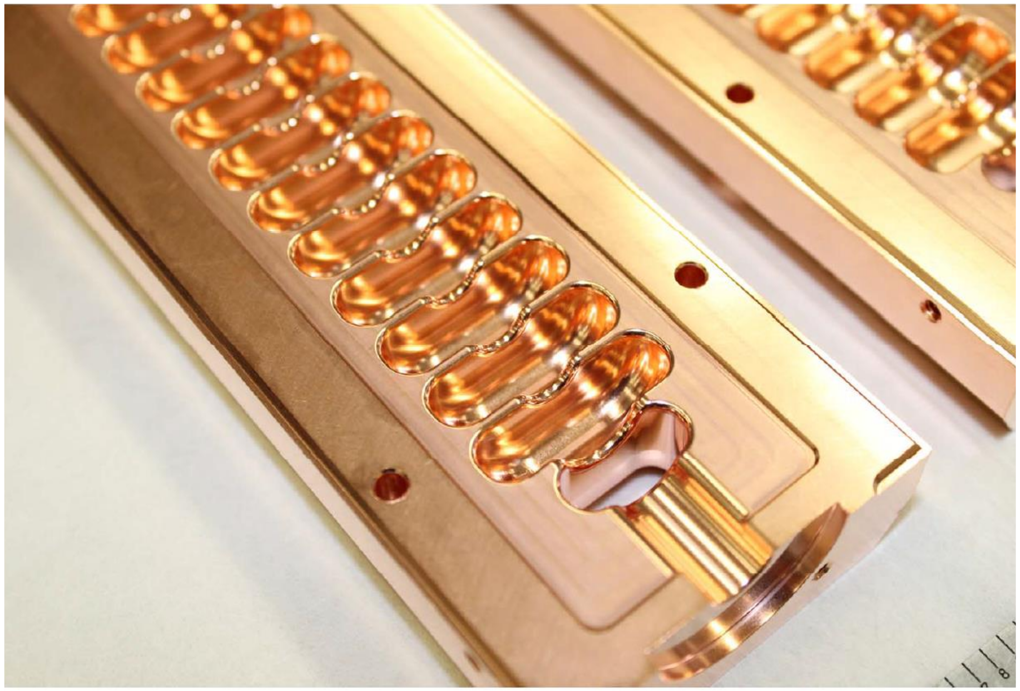
# Pulses	Equiv hours @50Hz	Run hours
238.9M	1327	2336.78

# Fake BDs	# BDs	Cluster BDs
35598	9940	5319

Mean BDR	Mean Cluster BDR
4.16E-5	2.23E-5

T. Argyropoulos, G. Giner, R. Rajamaki, B. Woolley

New directions – milled structures

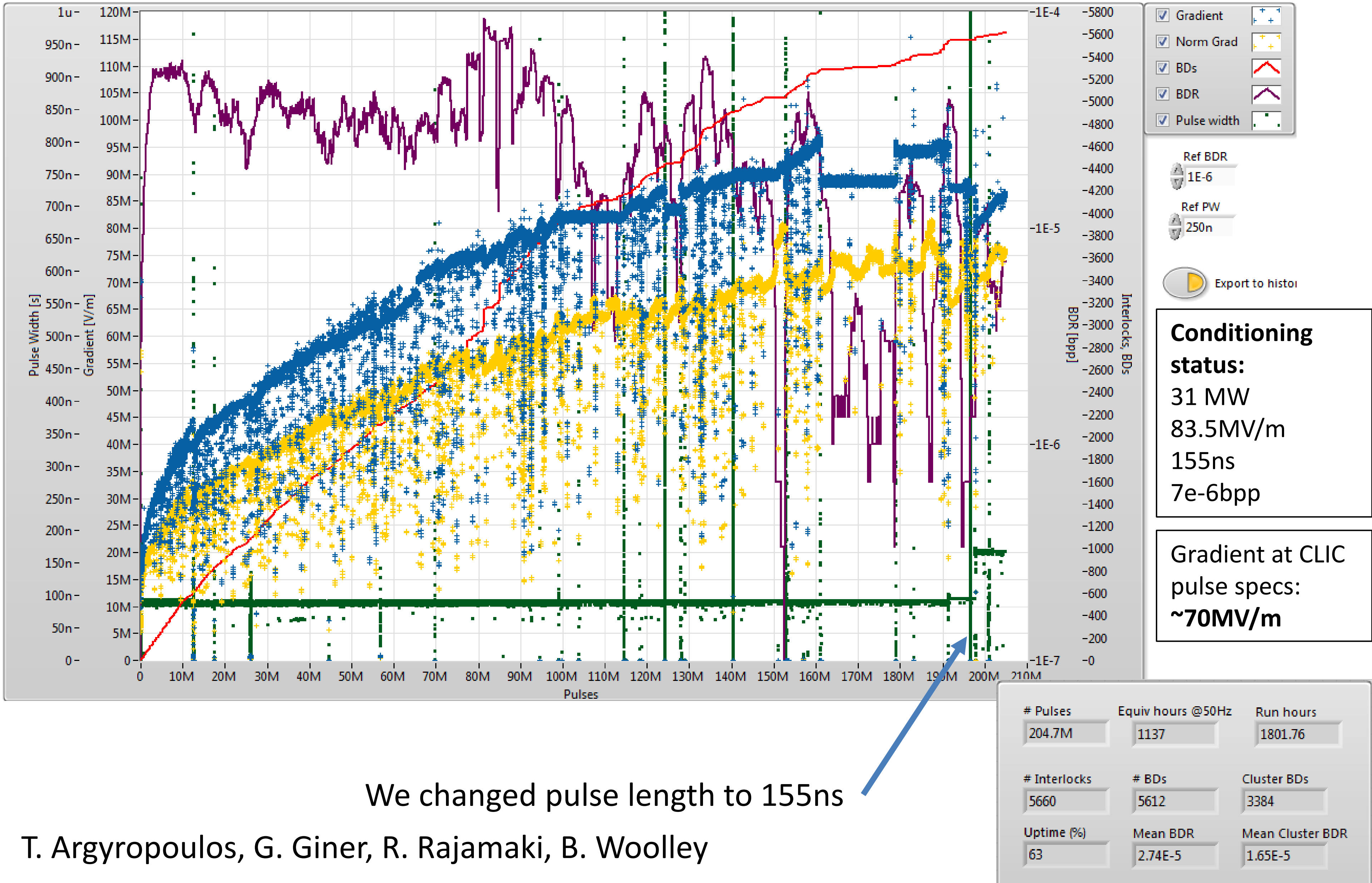


X-band structure in halves designed by CERN and built by SLAC

Milled structures have **huge potential advantages - cost, treatment, materials.** Early tries with quadrants yielded unsatisfactory results, but don't believe this was end of story. We're back!

A. Grudiev, H. Zha, V. Dolgashev

T24OPEN full history



Conditioning status:
31 MW
83.5MV/m
155ns
7e-6bpp

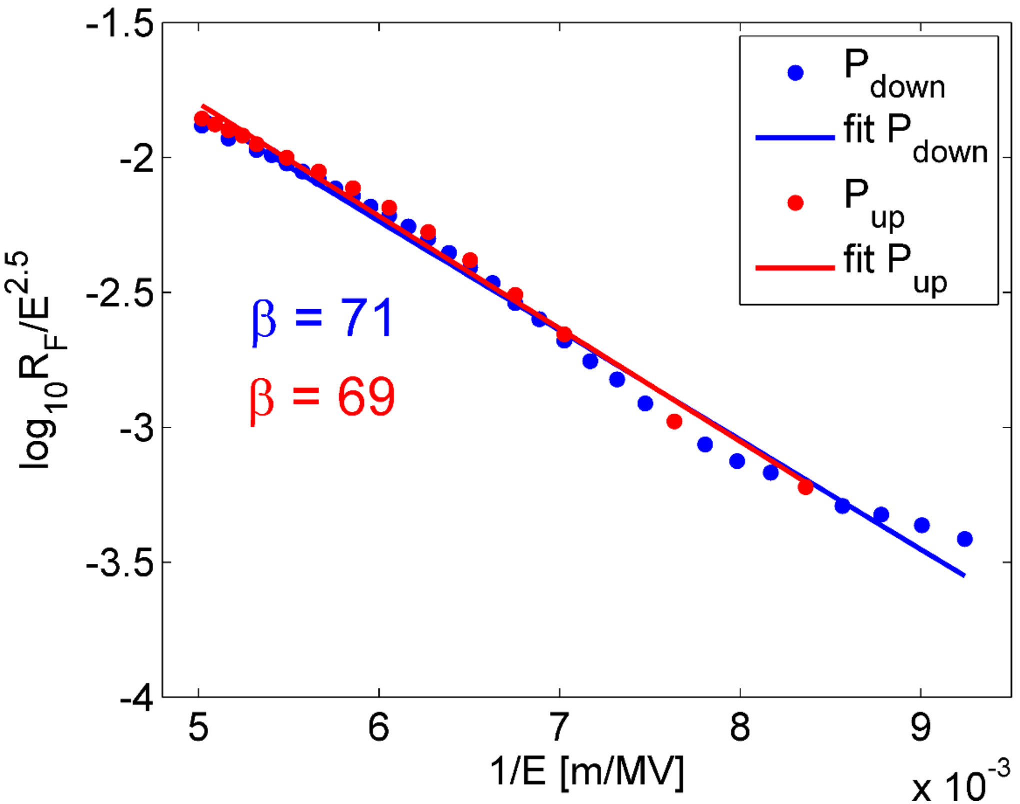
Gradient at CLIC pulse specs:
~70MV/m

We changed pulse length to 155ns

T. Argyropoulos, G. Giner, R. Rajamaki, B. Woolley

Radiation in Xbox-2 bunker

Fowler-Nordheim plot
We assume field emission current is proportional to the measured radiation in the bunker
PRELIMINARY.

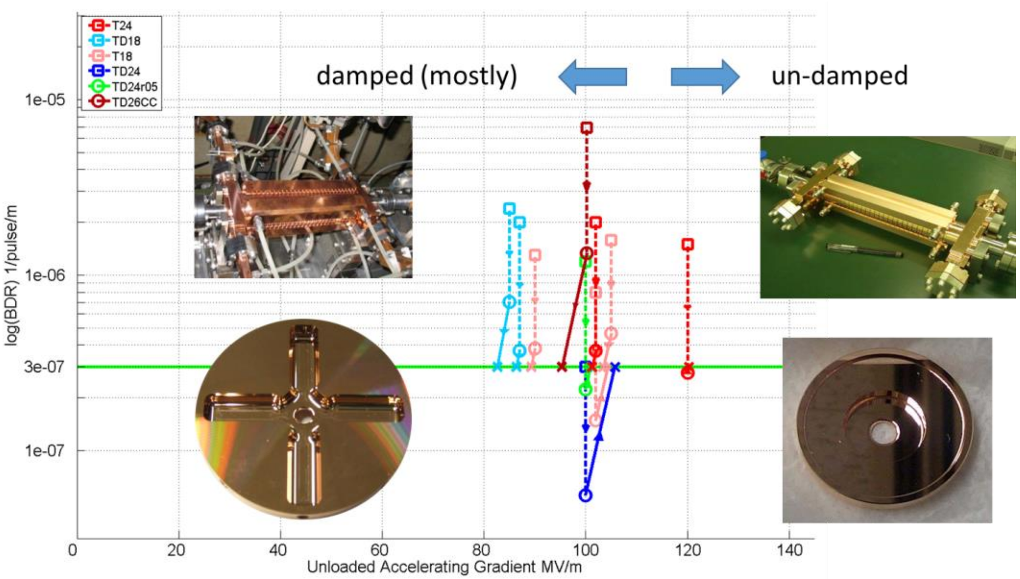


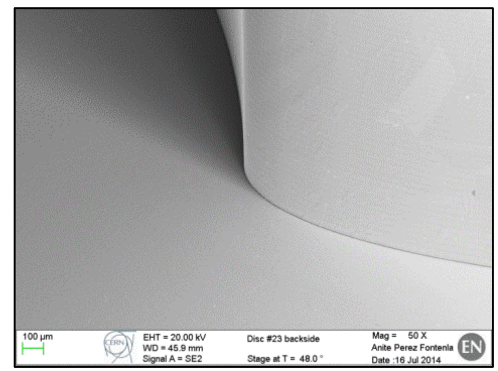
Faraday Cup signals are too low to measure field emission.

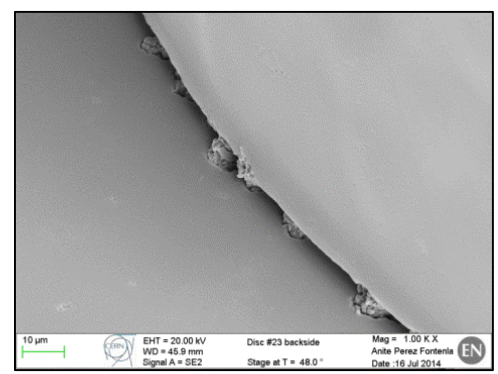
We plan to do a scan thi week in Xbox-1 using the diamond (now good signal!) detector installed next to the structure

120 MV around the corner for Full length prototypes

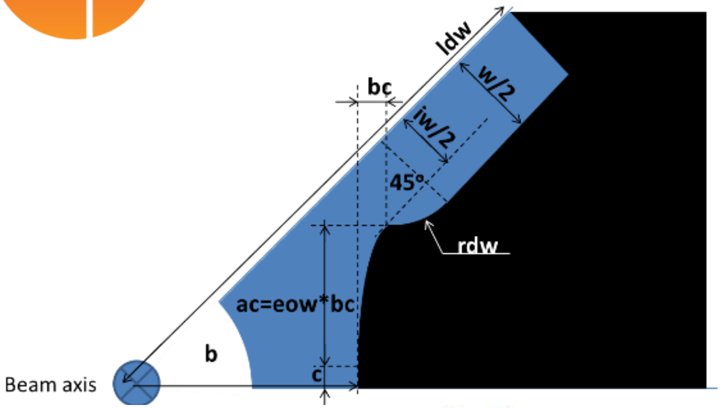
- We have shown 120 MV/m in an undamped, full length structure (no beam loading). We are now building more of these to validate the performance.
- There seems to be a loss of gradient from effects outside the high power flow and electric field region. Apparently due to technological mistake, excessive chamfer, addressed in new prototypes.

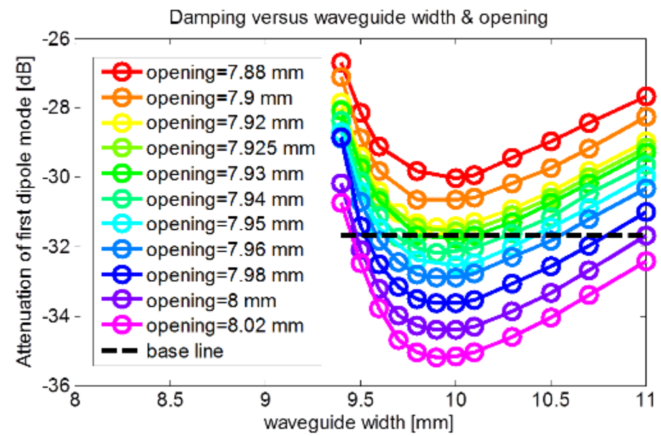


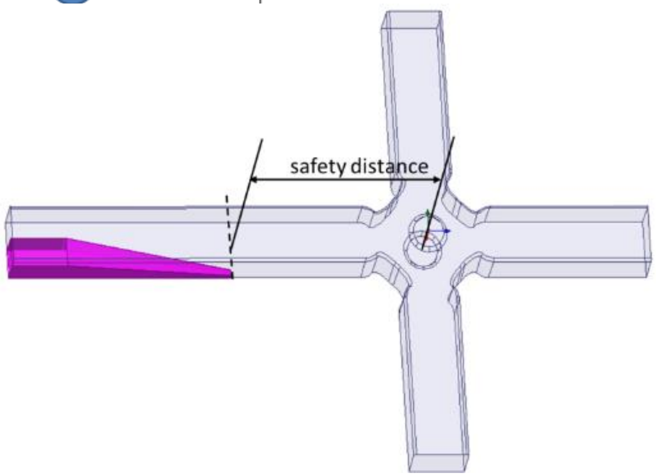


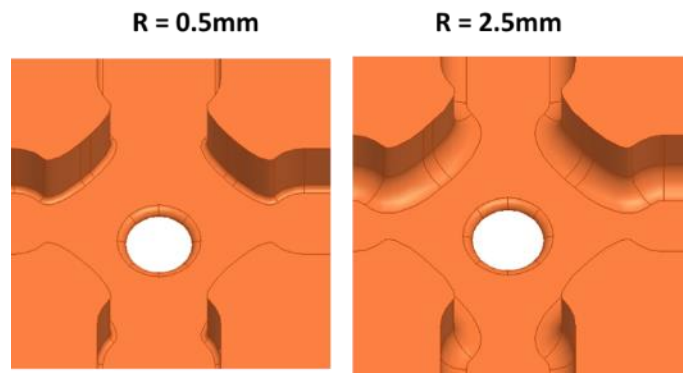


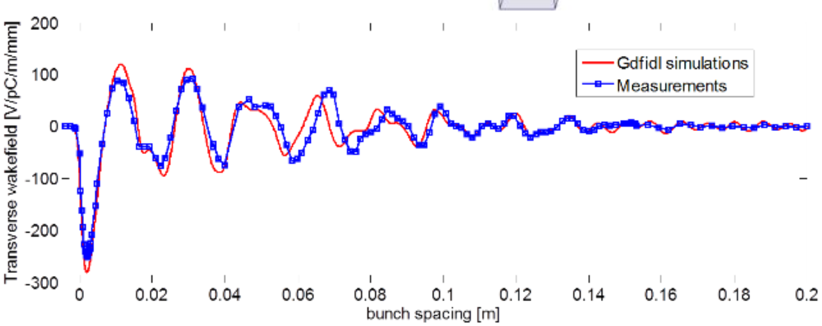
Progress in understanding and feedback on rf design

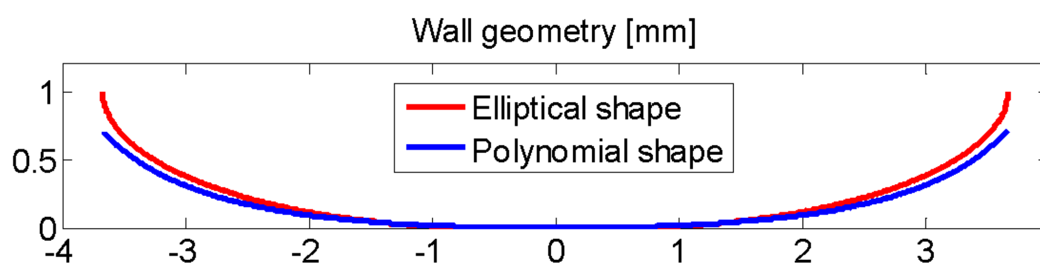










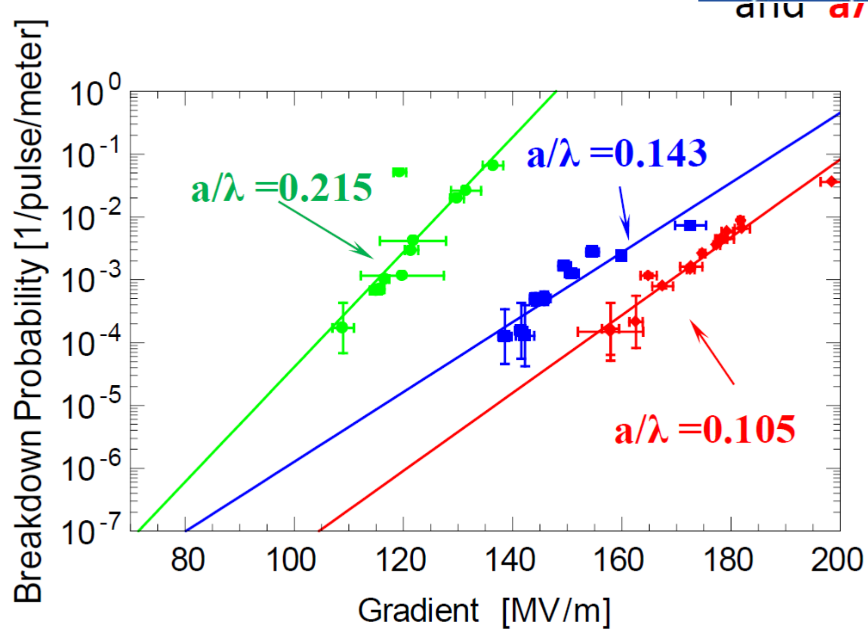


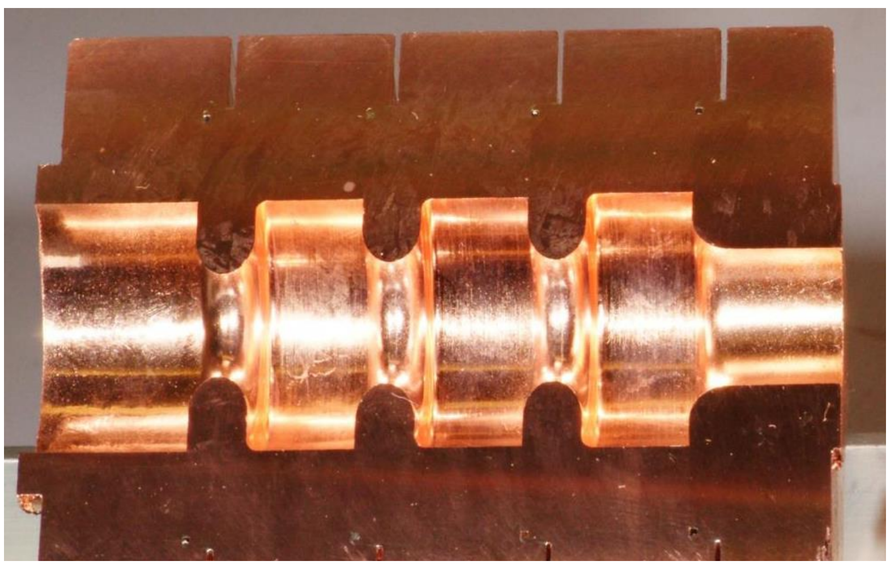
Single cells

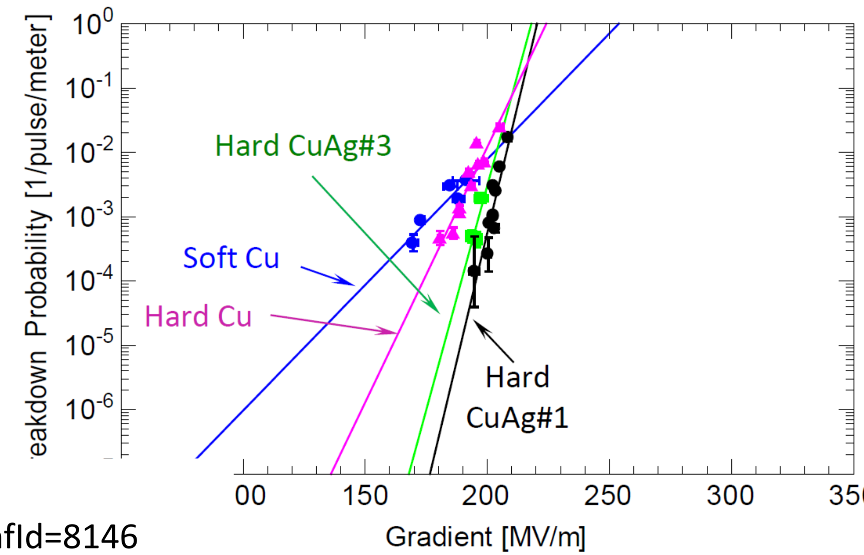
There's a hidden story behind the full structures which emerges when looking at single cells.

SLAC has a long-standing single cell testing program.

Gradients up to 200 MV/m are possible.



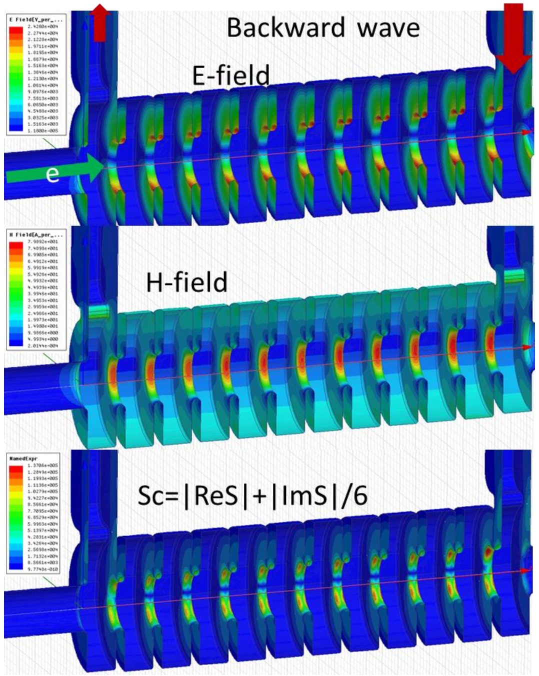


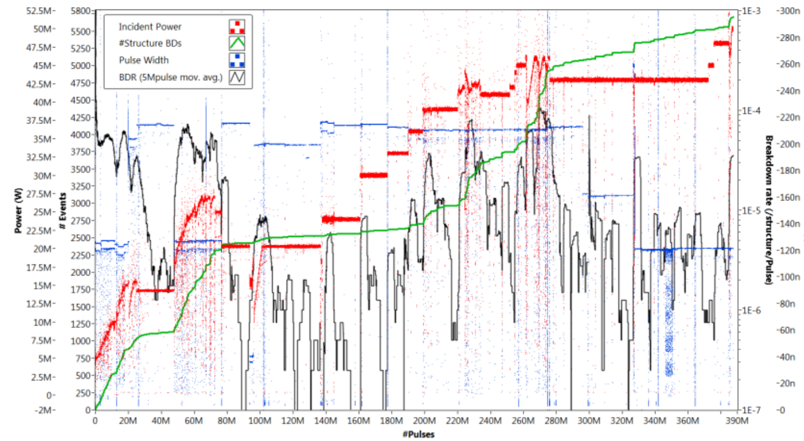


V. Dolgashev, EAAC2015

https://agenda.infn.it/contributionDisplay.py?contribId=227&confId=8146

Deflecting cavity





B. Woolley

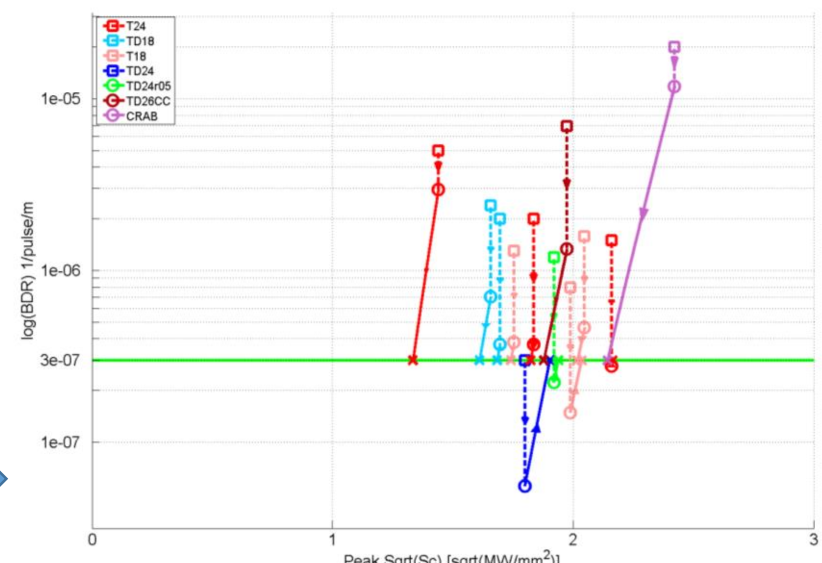
Up to 47 MW!

G. Burt

Lancaster crab cavity: rf design and installed in XBox-2.

2015

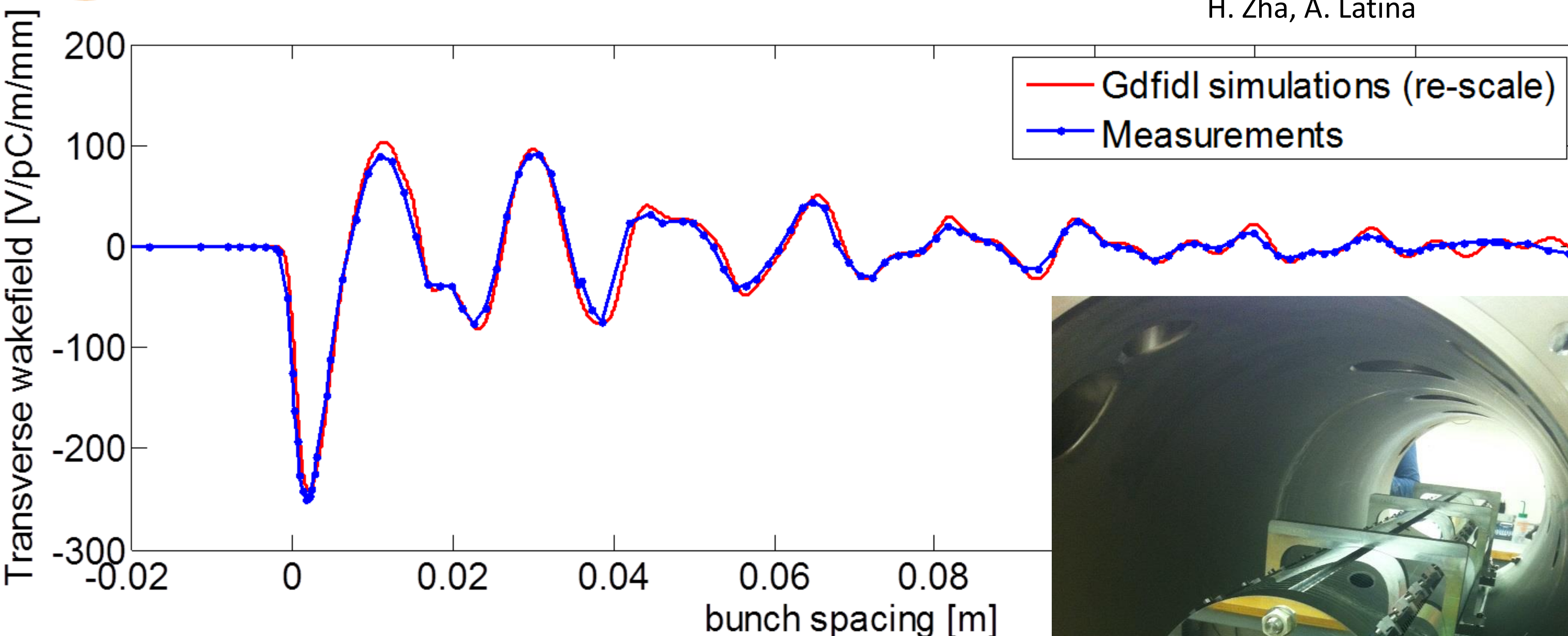
$TM_{1,1,0}$ dipole mode instead of monopole, still very consistent *Sc*, local power flow .

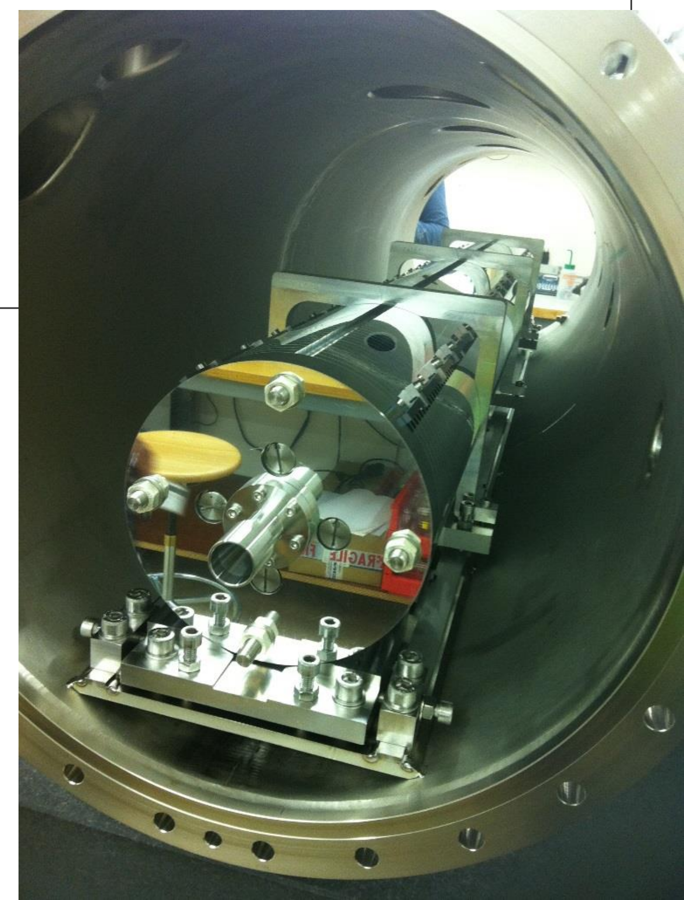


A. Degiovanni

Wakefield suppression

H. Zha, A. Latina





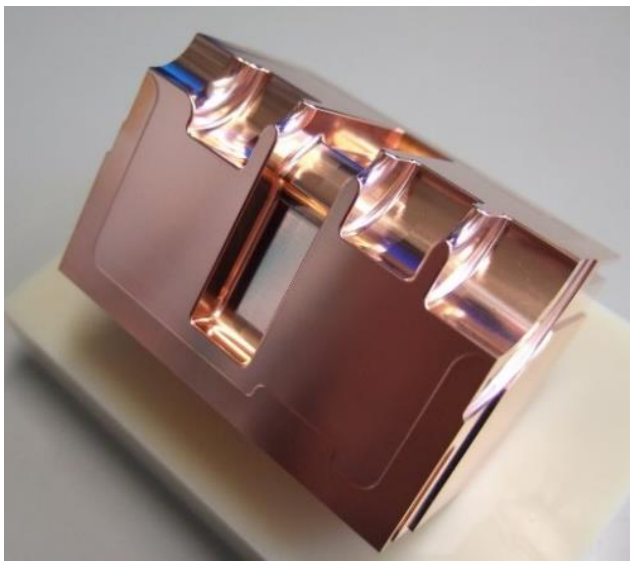
Wakefield from 1.5 m long, 6 structure length, prototype measured directly with beam at the FACET facility at SLAC.

The agreement between measurement and simulation is a spectacular validation of our design capabilities and we meet our beam dynamics requirements!

More wakefield suppression

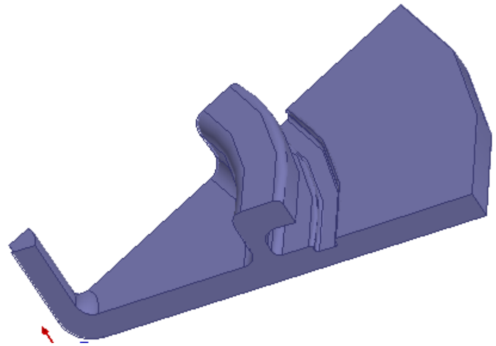
Ongoing development of alternatives for HOM damping.

T. Abe, T Higo

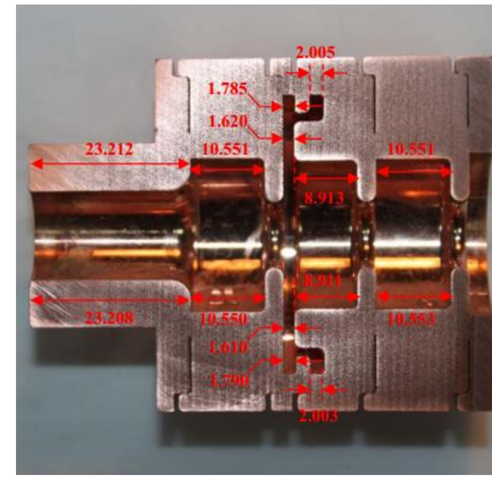


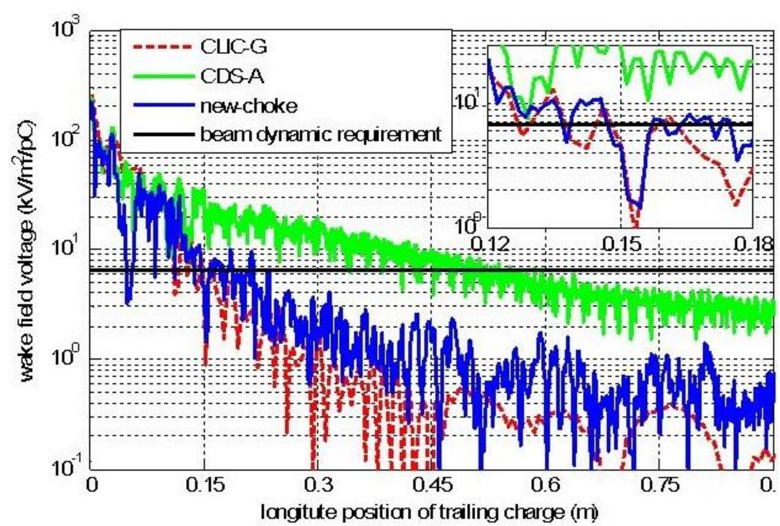
Quadrant structure development at KEK

J. Shi, H Zha



Choke-mode cavity, Tsinghua U. development





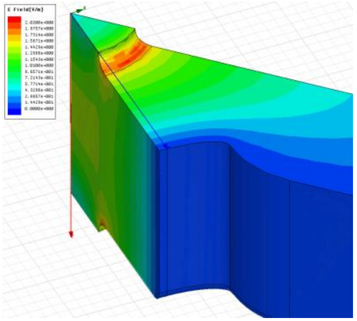
Understanding

RF design for high gradient

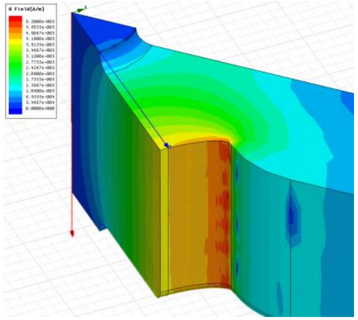
We have well developed rf design criteria which **predict the gradient** of pulsed high-gradient structures. The criteria cover the physical phenomena which limit accelerating gradient:

- Power flow
- Surface electric field
- Surface magnetic field/pulsed surface heating

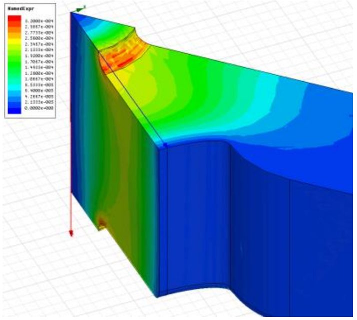
E_s/E_a

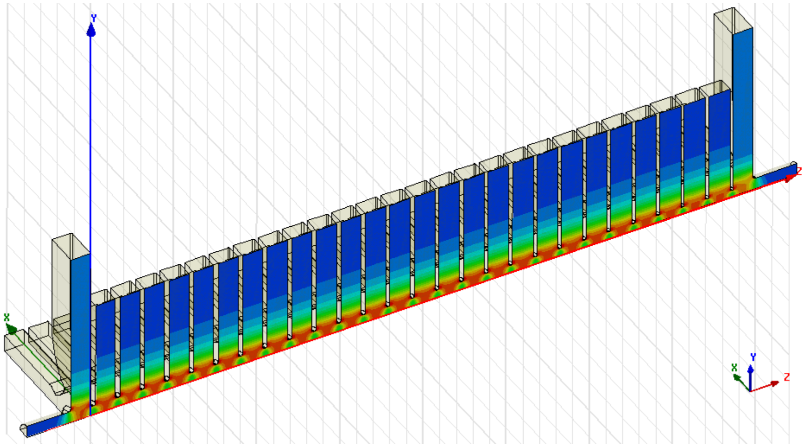


H_s/E_a



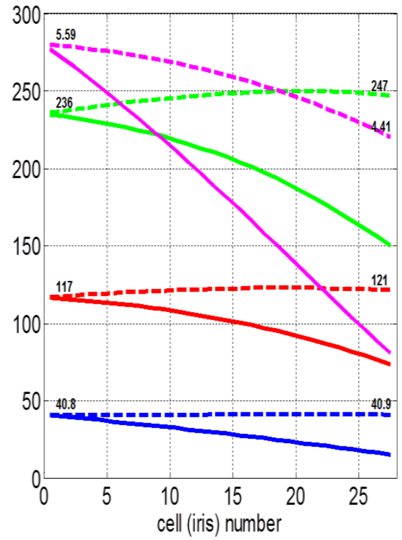
S_c/E_a^2





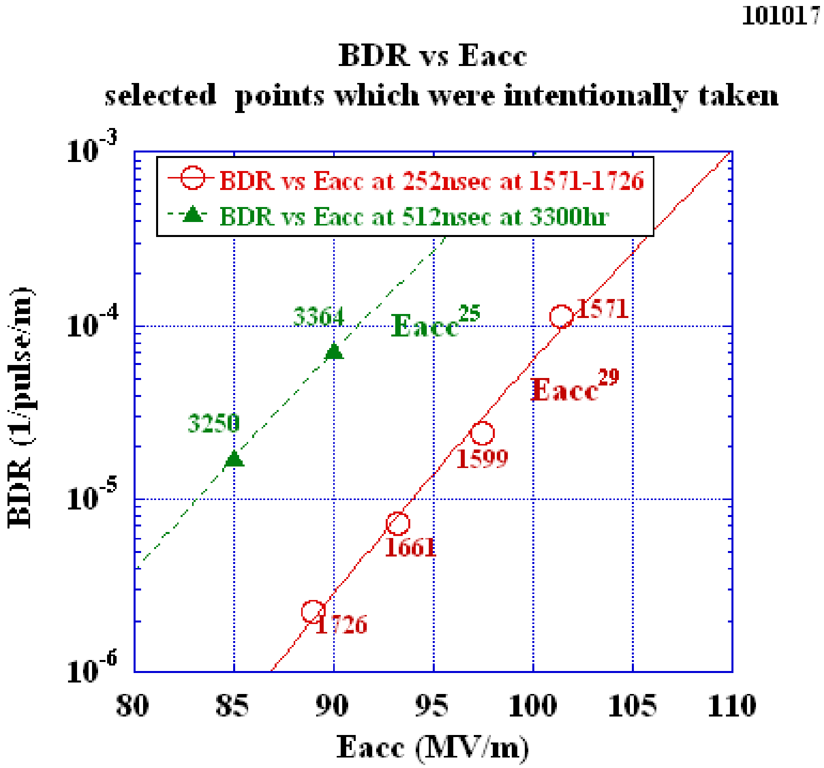
New CLIC 3 TeV baseline

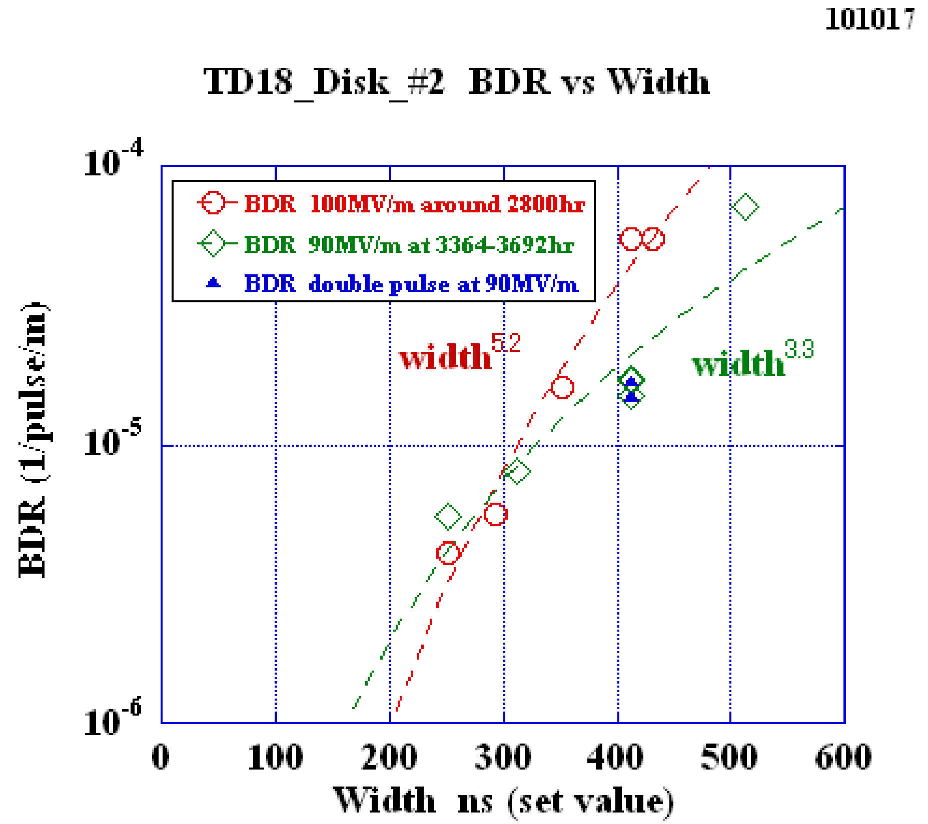
H. Zha, A Grudiev



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

Important dependencies





T. Higo

For a fixed pulse length

$$BDR \sim E_a^{30}$$

For a fixed BDR

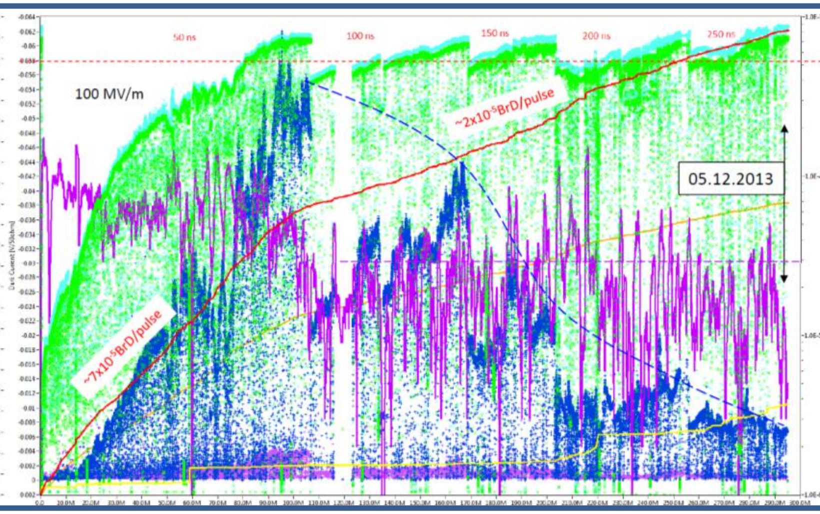
$$E_a \cdot t_p^{1/6} = const$$

$$\frac{E_a^{30} \cdot t_p^5}{BDR} = const$$

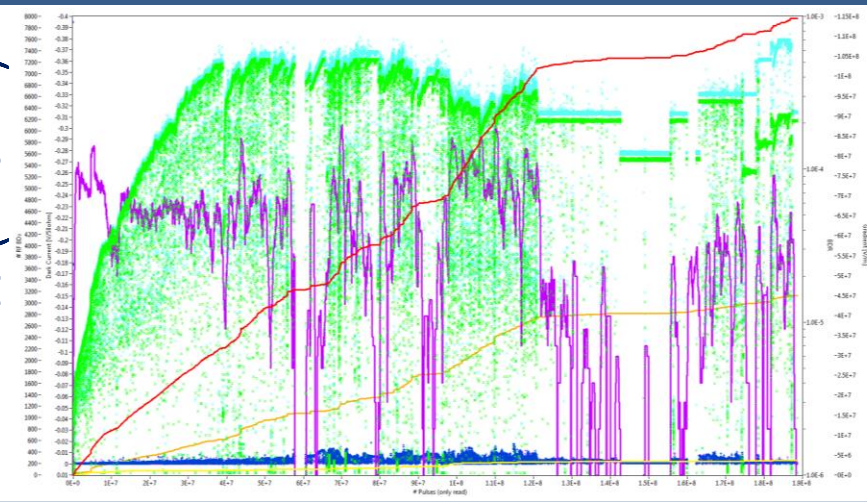
Collection of conditioning histories

CLIC damped (TD) structures

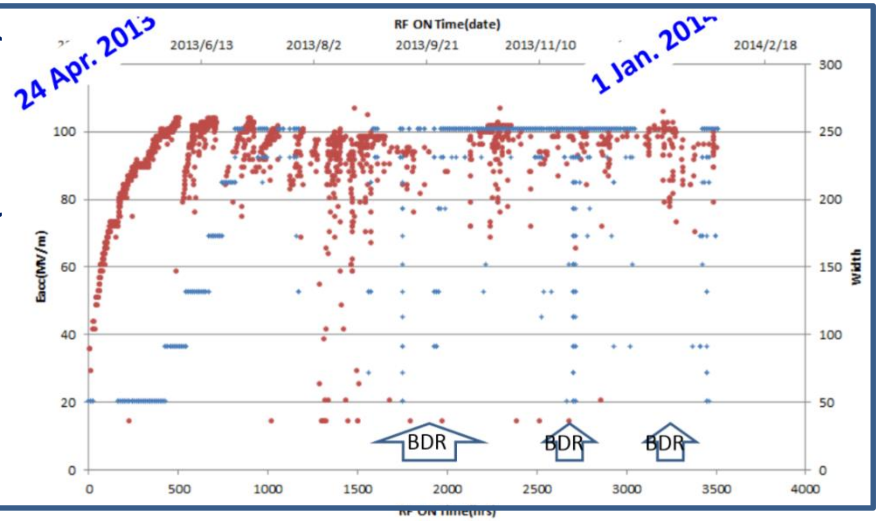
TD26CC (XBOX-1)



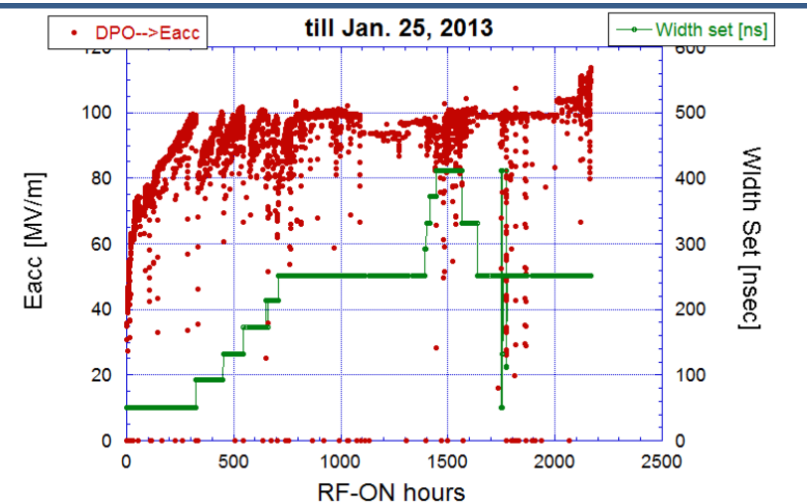
TD24R05 (XBOX-1)



TD24R05#4 (NEXTEF)



TD24R05#2 (NEXTEF)



Scaling: description of conditioning state

TD26CC#1 scaled gradient

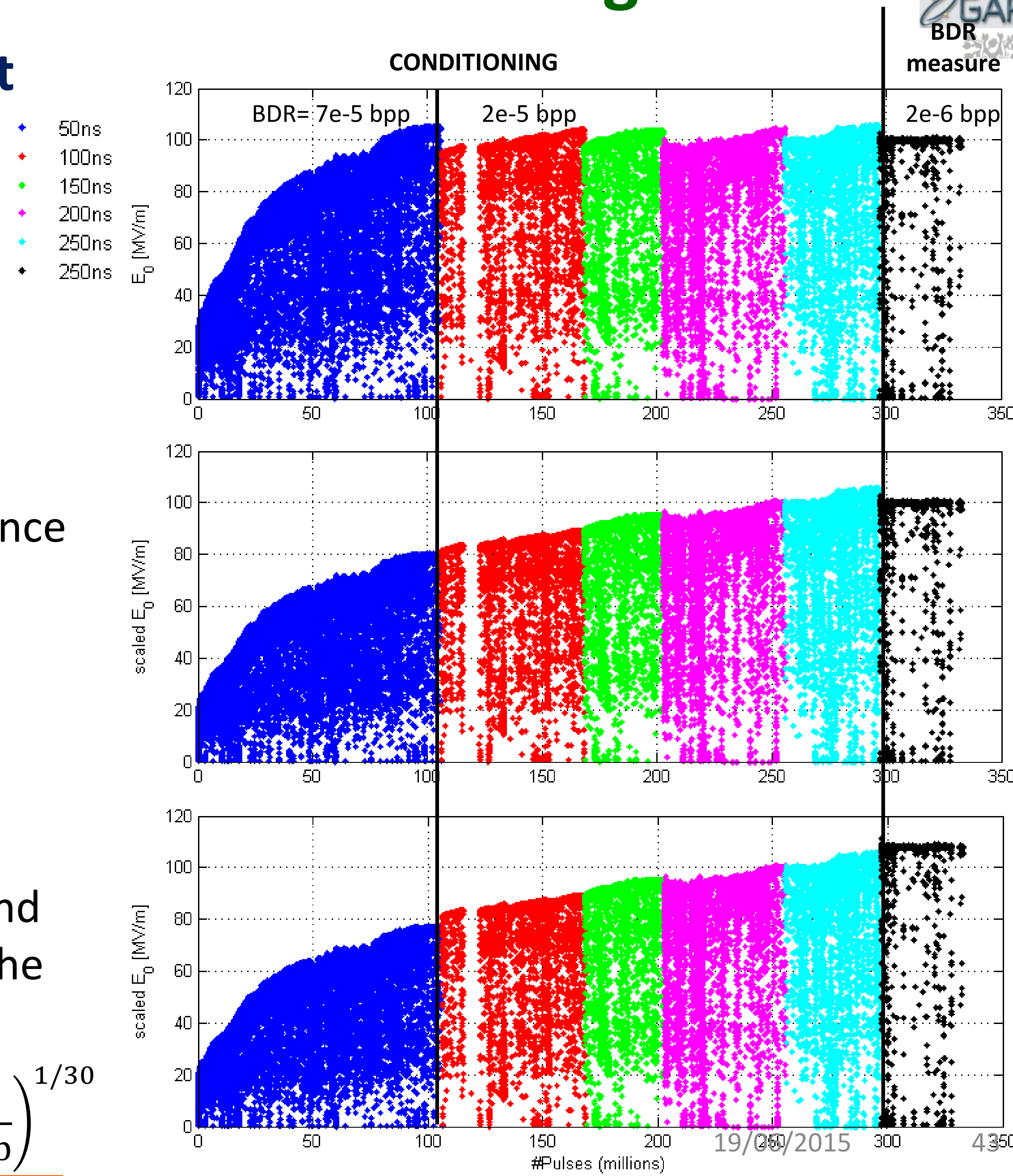
Raw data full history

Equivalent gradient curve with constant pulse length of **250ns** since the beginning

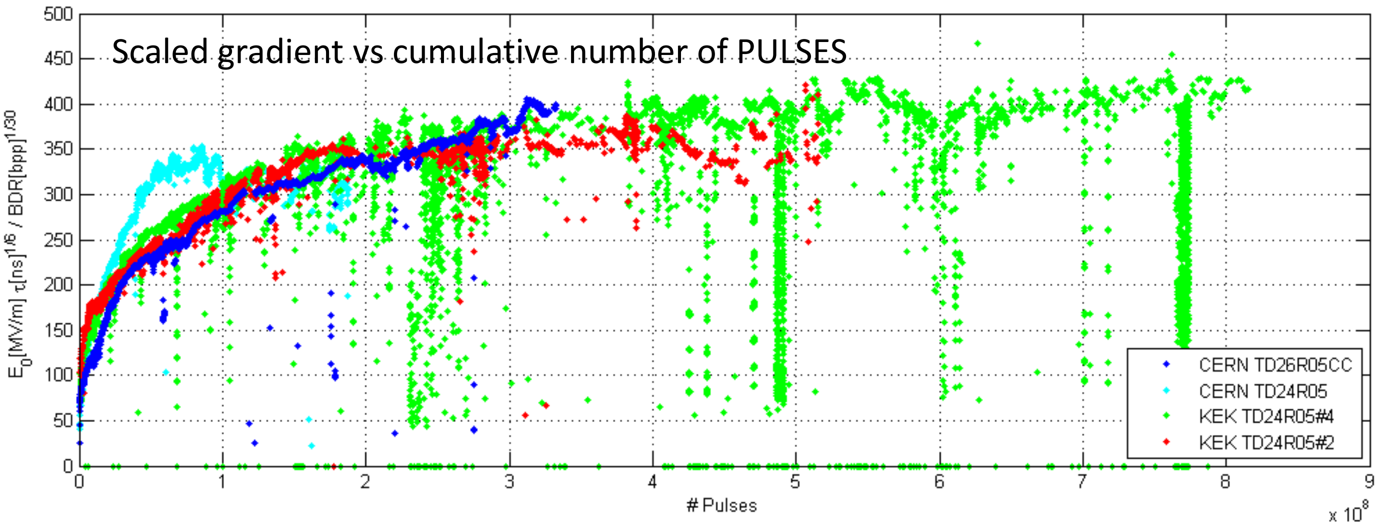
$$E_0^{scaled} = E_0 \left(\frac{t_p}{250\text{ns}}\right)^{-1/6}$$

Equivalent gradient curve with constant pulse length of **250ns** and constant BDR of **2e-5 bpp** since the beginning

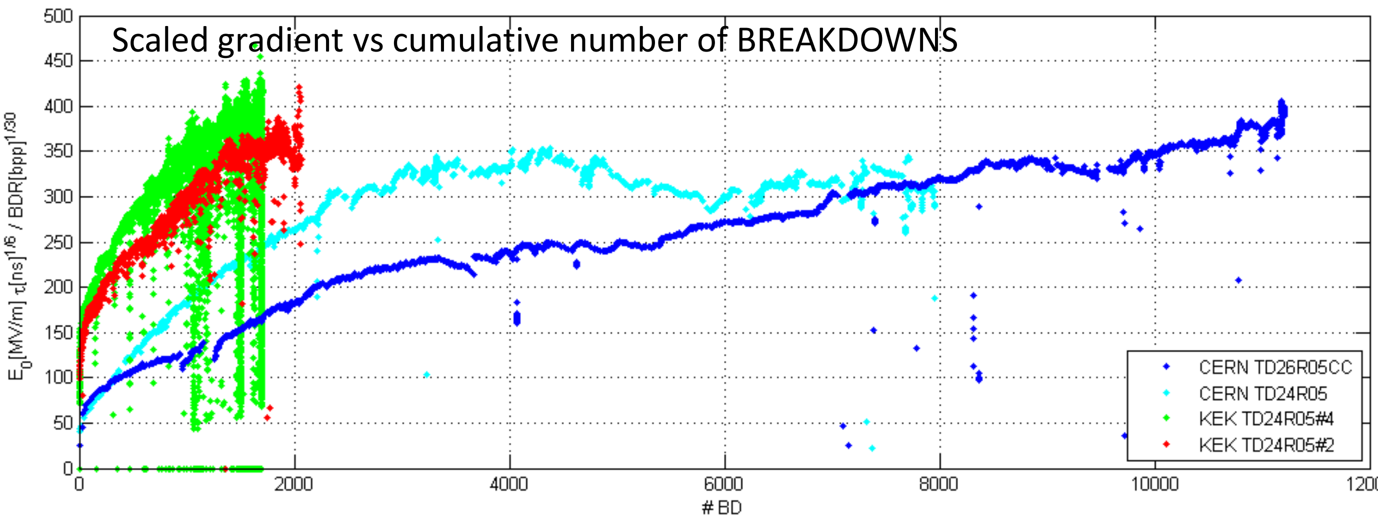
$$E_0^{scaled} = E_0 \left(\frac{t_p}{250\text{ns}}\right)^{-1/6} \left(\frac{\text{BDR}}{2\cdot 10^{-5}\text{bpp}}\right)^{1/30}$$



Now comparing structures



Pulses

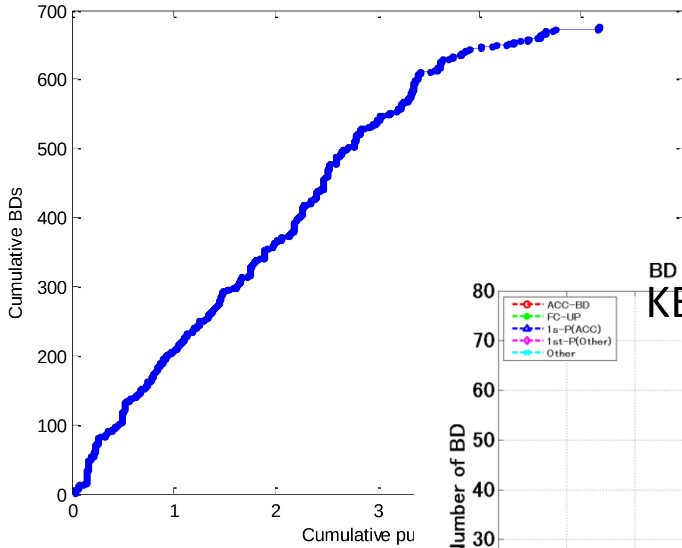


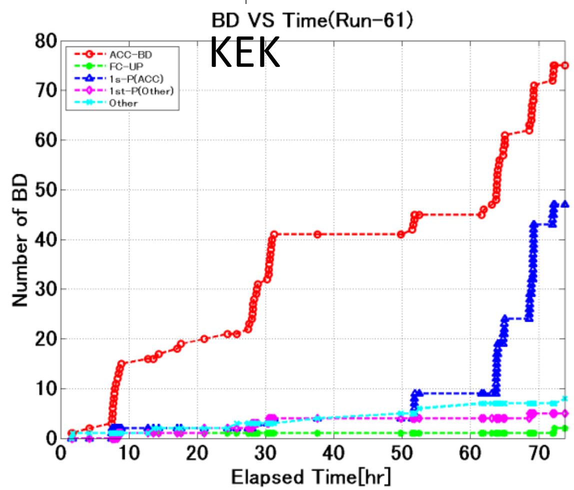
Breakdowns

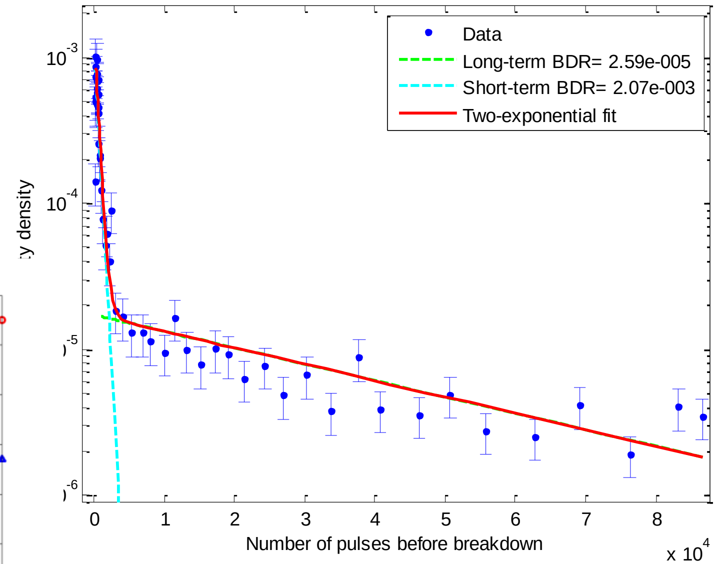
Breakdown statistics

J. Giner, A. Korsback

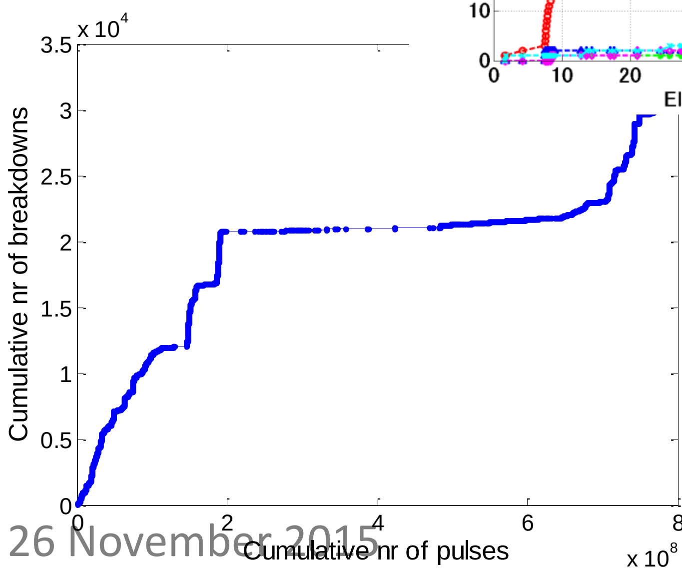
rf

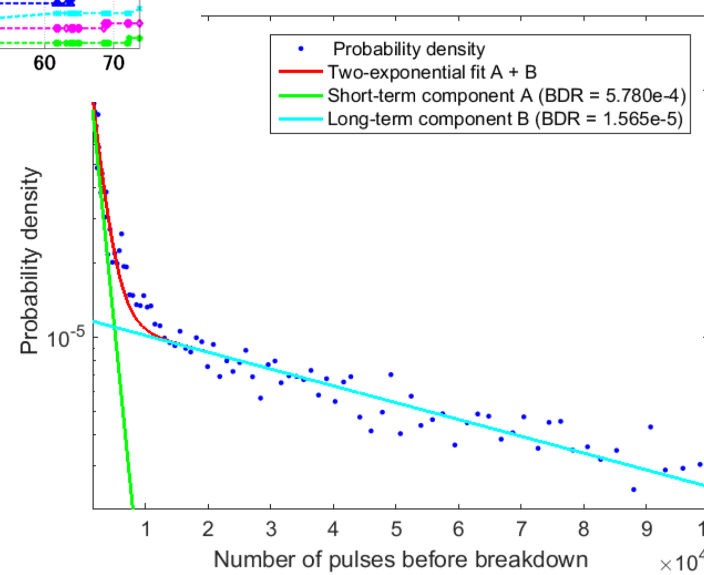






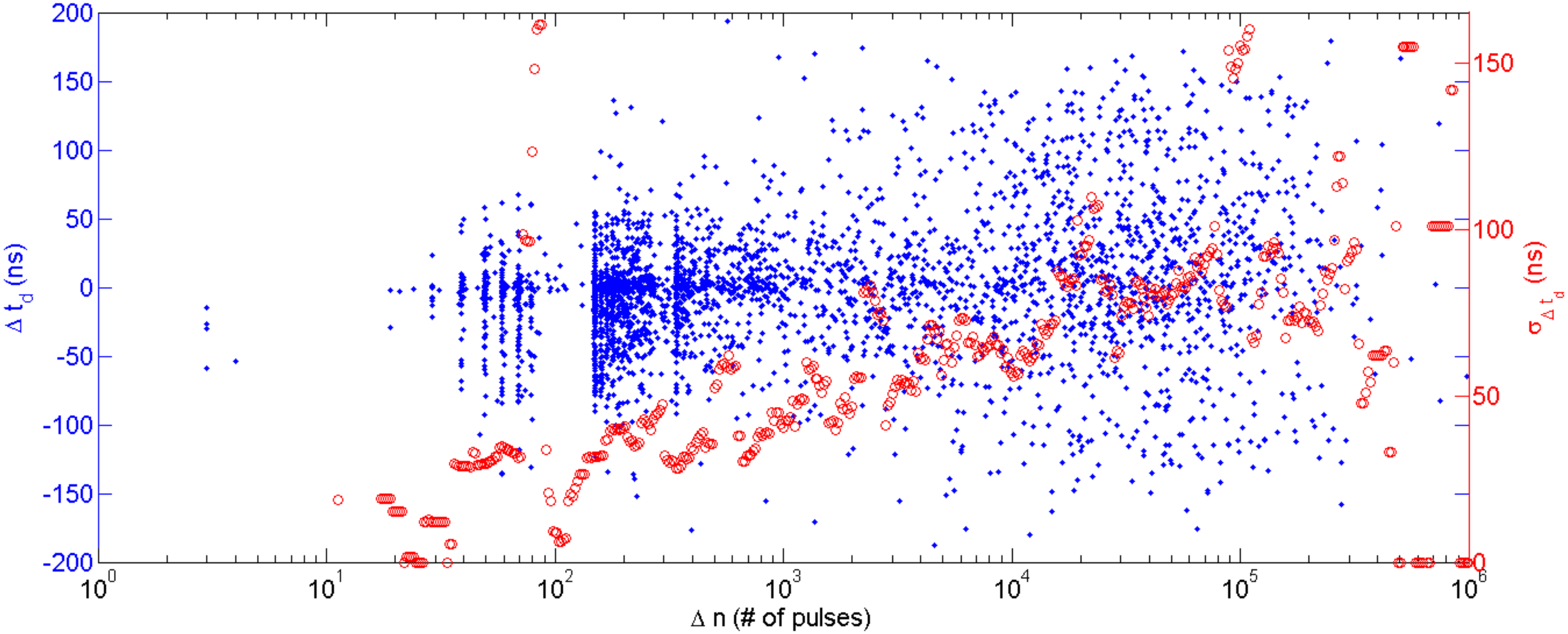
dc





Correlation between breakdowns

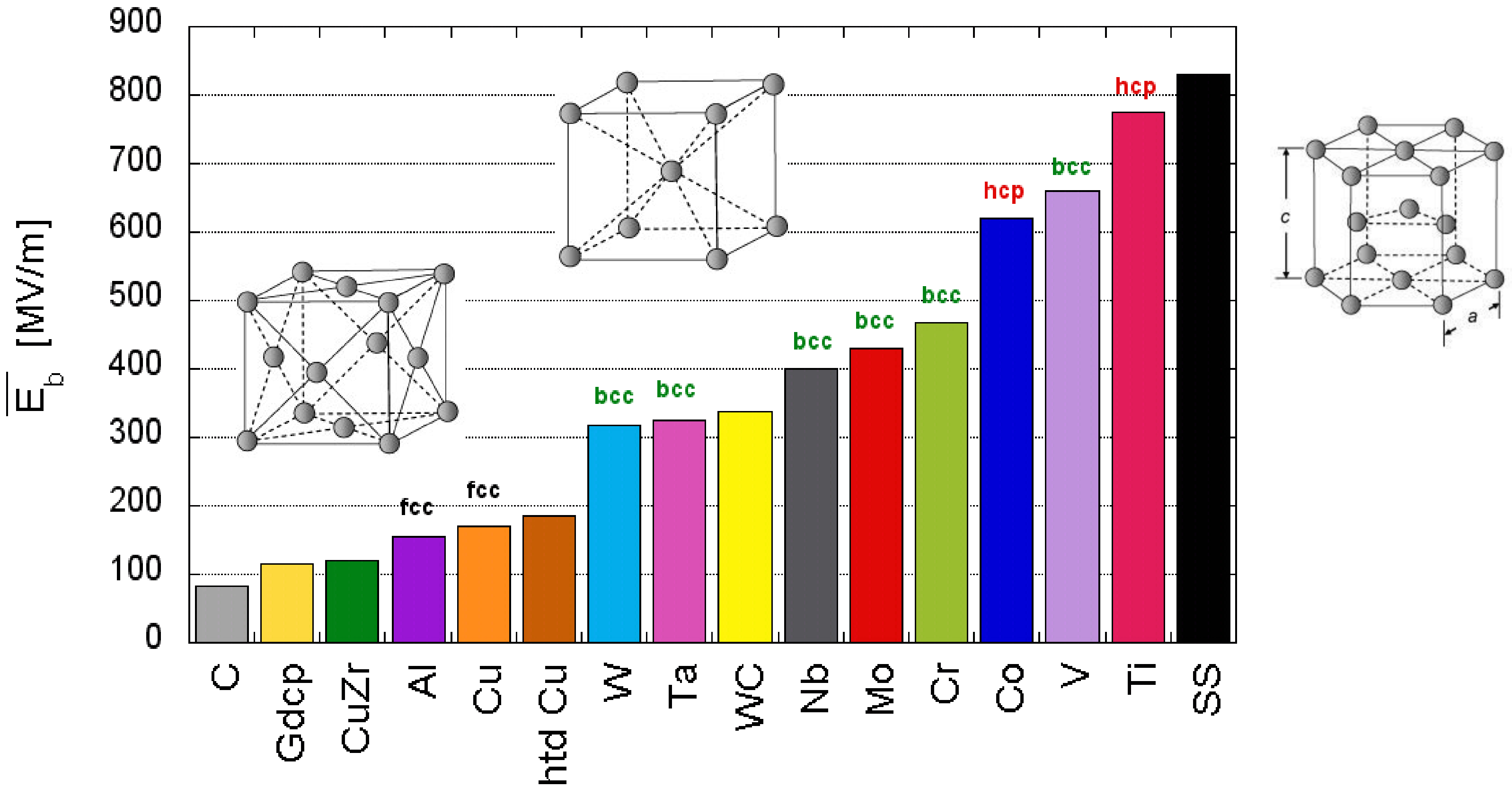
Distance between successive breakdowns



R. Rajamaki

Number of pulses between successive breakdowns

Material dependence in pulsed dc

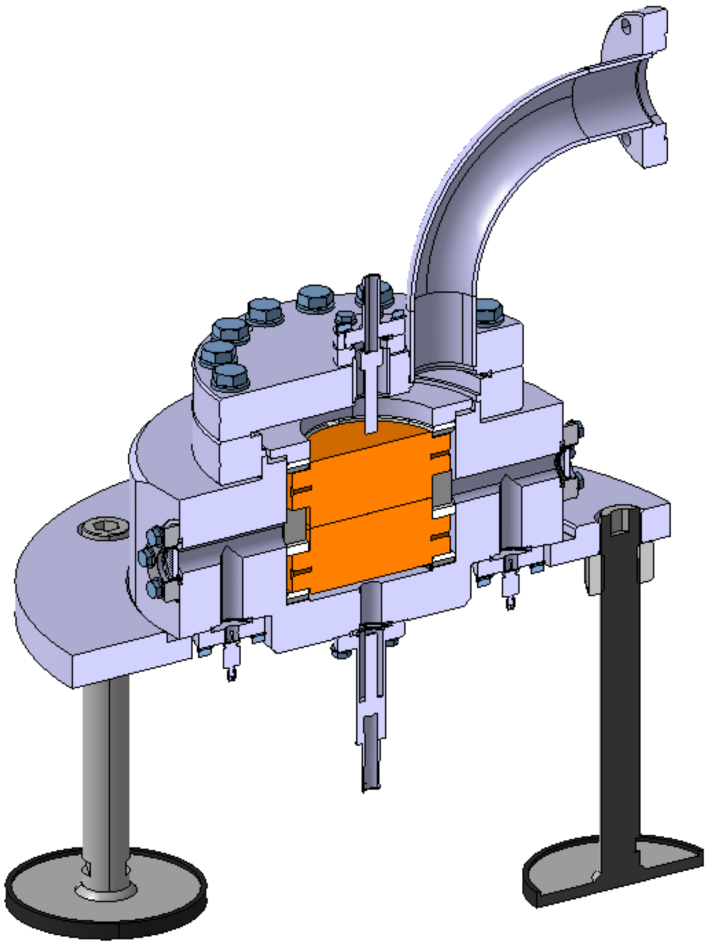


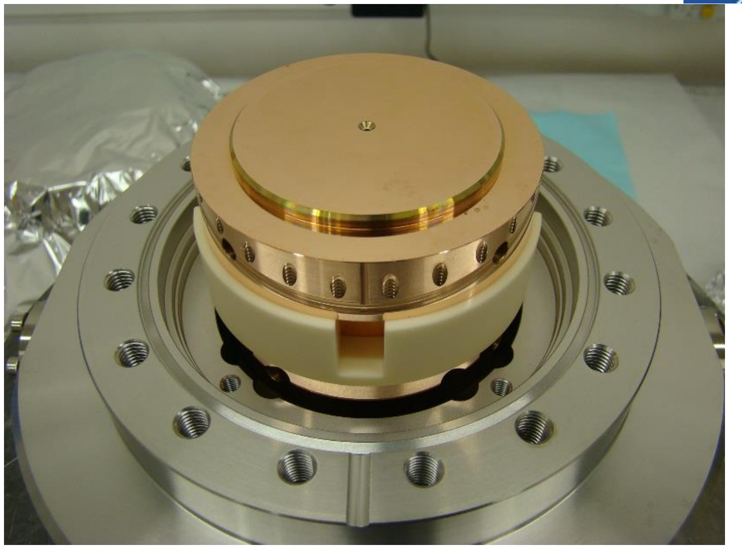
A. Descoeudres, F. Djurabekova, and K. Nordlund,
DC Breakdown experiments with cobalt electrodes,
CLIC-Note 875, 2011

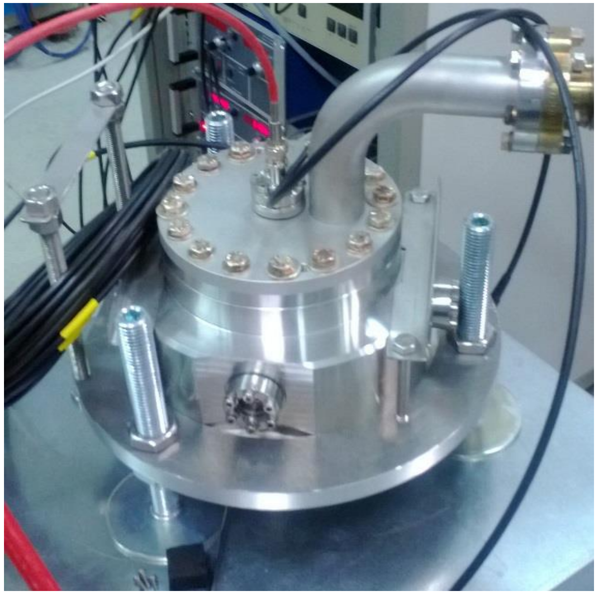
Hardware status and evolution: Large area electrodes

62 mm diameter electrodes separated by precision ceramic spacer, gaps between 10 and 60 µm. Very large surface both compared to breakdown crater size and high field region in rf cavities allows study of effects of production (machining, heat treatment, chemistry) and operation (conditioning, breakdown statistics) related issues.

Vacuum chamber

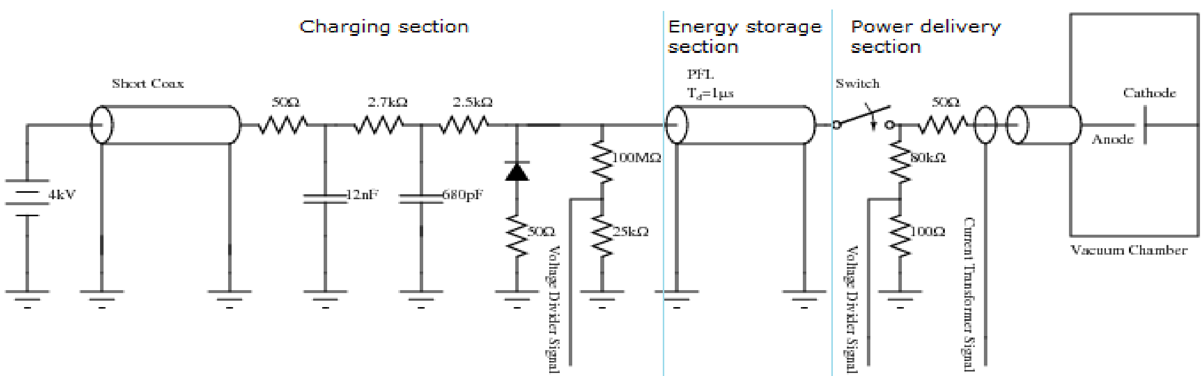


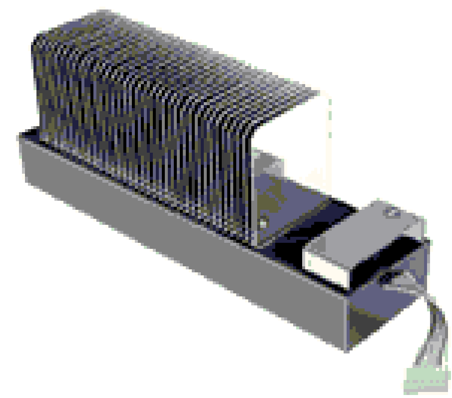


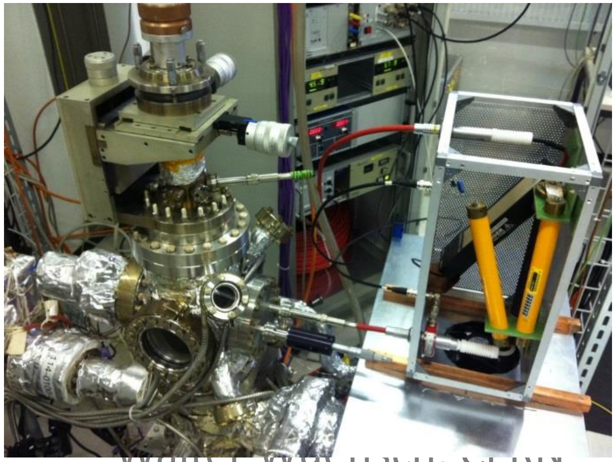


High repetition rate, high-voltage pulser

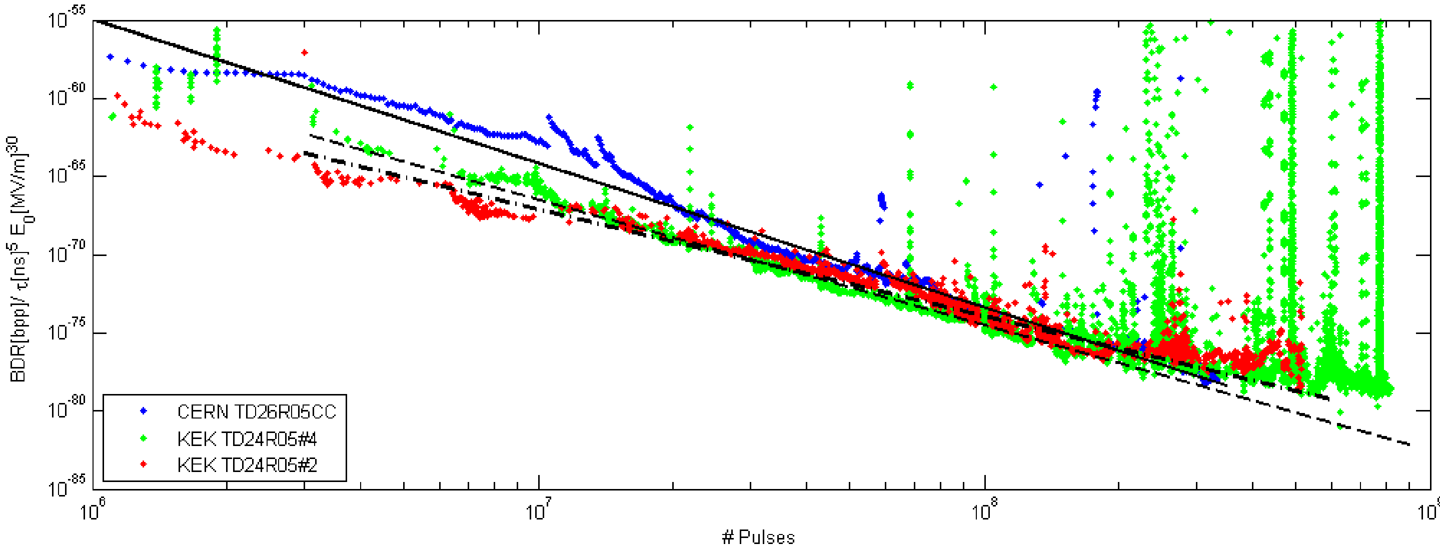
We now use a MOSFET-based commercial switch, which allows us to pulse up to 1 KHz with pulse lengths from 1 to around 8 µs (followed by exponential decay).





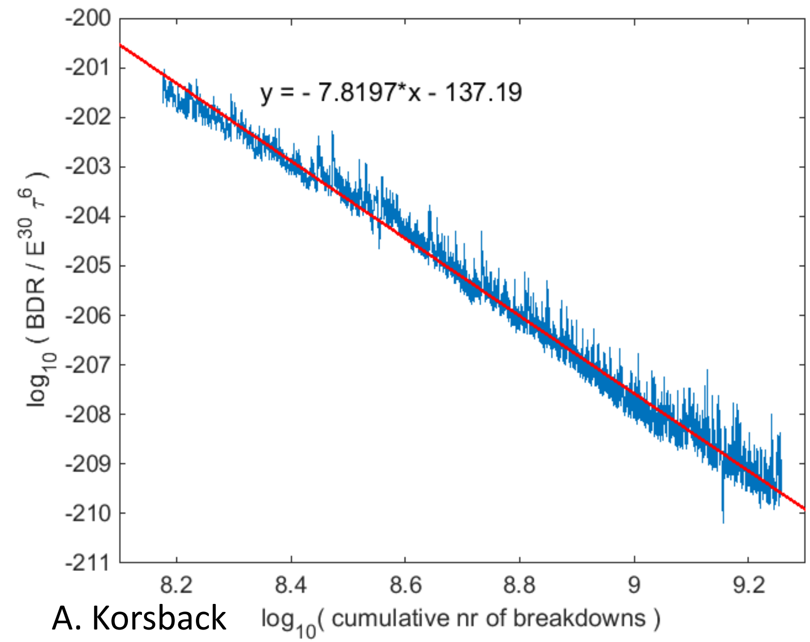


Pulsed dc and rf comparison



Our insight: pulses condition the structure rather than breakdowns.
What is the mechanism? Seems to be a hardening process.
Figuring this out could help us pre-process out structures and reduce conditioning time.

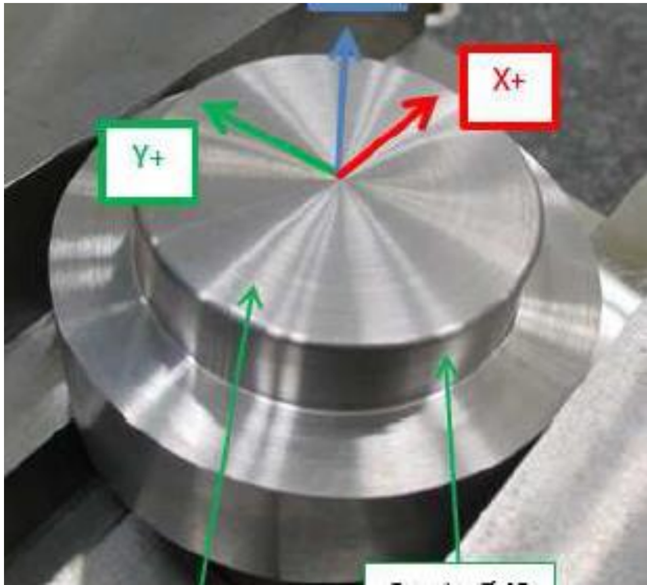
CERN pulsed dc system



A. Korsback

Outlook – scientific program

- optimization of production – multi-sample program for machining, chemistry and heat treatment.
- Optimization of conditioning strategy
- Electrodes for INFN to optimize chemical treatment of non-brazed rf photoinector
- Investigate high electric field behaviour of Ti 3-D printed electrodes to support printed rf component development.
- Re-heat of conditioned cathodes to determine mechanism of conditioning.
- Time structure of field emission.
- Nb electrodes
- Integrate dynamic vacuum measurement
- Surface microscopy



Outlook – hardware development

- Marx generator for fast rise *and* fall time. Good for pulse length dependence and comparison to rf.
- 2^{nd} large electrode chamber
- Cool-able, 4.2 ^{o}K, system: To test high-peak power processing for superconducting cavities, high-field material dependence (Cu is FCC, Nb is BCC, field emission and BDR as a function of temperature.

Dislocation dynamics and criticality – Hebrew University of Jerusalem

Dislocation mediated – self organized criticality

Plasticity of Micrometer-Scale Single Crystals in Compression

Michael D. Uchic, Paul A. Shade, and Dennis M. Dimiduk

Single crystal micro-pillar compression:
Dislocation mediated intermittent flow - size effects, hardening.
Dislocation density inside a plane as a controlling parameter.

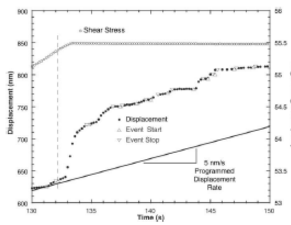
Intermittency characterized by a universal Power law burst PDF

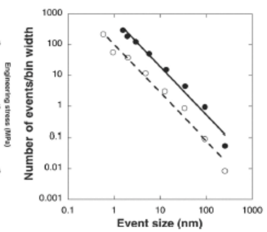
Acoustic emissions: Similar + space and time coupling between events

(Weiss & Marsan, Science 2003)

Earthquakes show similar PDF and spatio-temporal correlation

(Kagan, Geopgysical J. (2007)

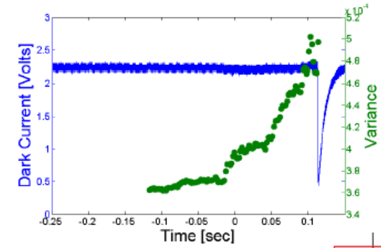




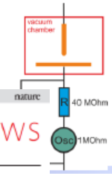
Uchic, Shade & Dimiduk, Annual Review
Dimiduk, Woodward, LeSar & Uchic: "Sc… Plasticity." Science (2006) 1188.

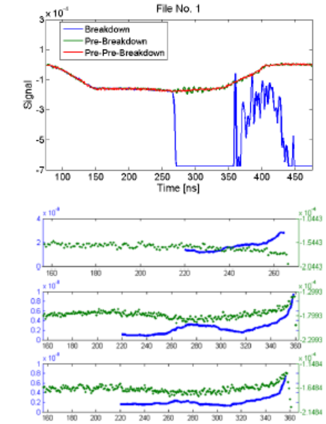
Observations until now...

- DC and RF indications of pre-breakdown increase in dark current variance



DC data





RF data - Alberto Degiovanni

PRE-BD signals

- As the system approaches the critical point. Fluctuation diverge.
- Observable through standard deviation of the time correlation

$$SD(t) = \frac{\int_{t\square\square}^{t+\square} (I(t)\square < I >)^2 dt}{(< I >)^2}$$

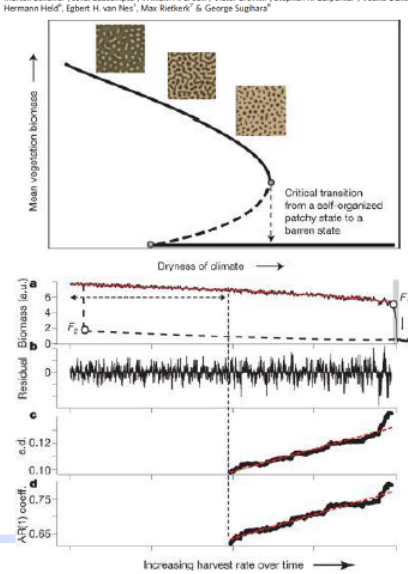
- Or, more generally, autocorrelation in the signal

$$R(k) = \frac{\int_0^{t\square k} (I(t)\square < I >)(I(t+k)\square < I >)dt}{\int_0^{t\square k} (I(t)\square < I >)^2 dt}$$

REVIEWS

Early-warning signals for critical transitions

Marten Scheffer, Jordi Bascompte, William A. Brock, Victor Brovkin, Stephen R. Carpenter, Vasilis Dakos, Hermann Held, Egbert H. van Nes, Max Rietkerk & George Sugihara



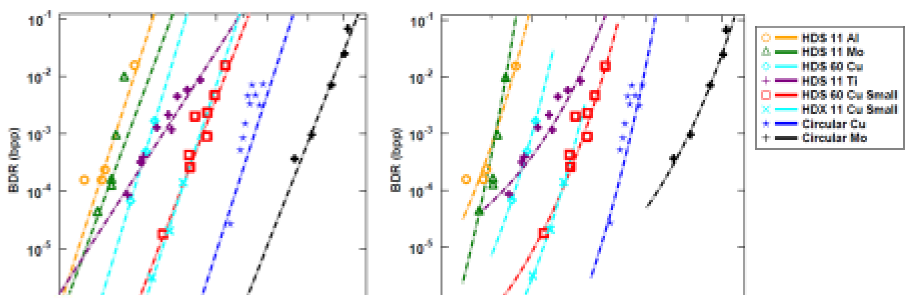
Atomistic simulations – University of Helsinki

Dislocation-based model for electric field dependence

- Now to test the relevance of this, we fit the experimental data
- The result is:

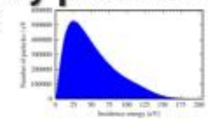
$$BDR = AE^{29} \qquad BDR = Ae^{\varepsilon_0 E^2 \Delta V / kT}$$

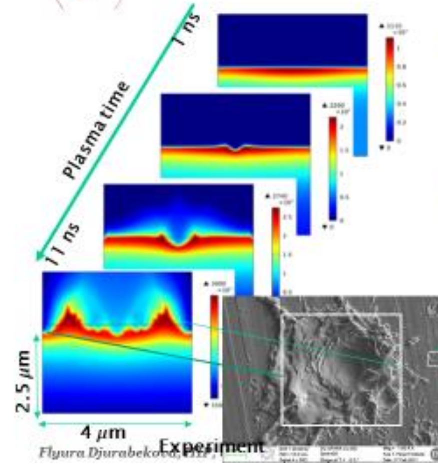
Power law fit — Stress model fit



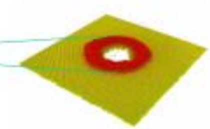
Surface damage by plasma ions

Plasma ions (from actual PIC calculations):
E_{ion} = 55 eV
flux = 5×10^{24} ion cm^{-2}s^{-1}



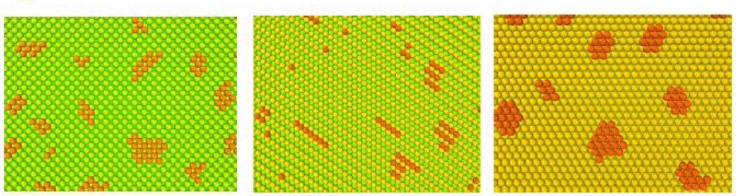


- By combining two methods, MD and FEM, we can clearly distinguish between the regimes of crater formation and splashes (liquid phase instabilities) after the breakdown event (left).
- Small size craters can be formed by the undeveloped plasma (sputtering yield (atom/ion) is less than 1) (bottom left)



(100), (110) and (111) surfaces

Kimocs simulations: Adatom islands



(100) (110) (111)

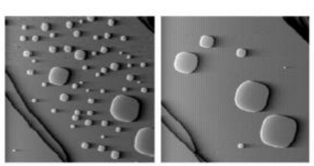
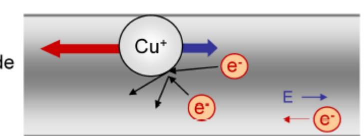


FIG. 2. Two 300 nm × 300 nm STM images, separated in time by 20 000 s, showing island ripening on Cu(001) at 343 K.
[J.B. Hannon et al. PRL 1997]

Effective charge



$$F = E_{\text{int}}(Z_d + Z_w) = E_{\text{int}} Z^*$$

Direct Ion valence — Wind valence — Effective valence

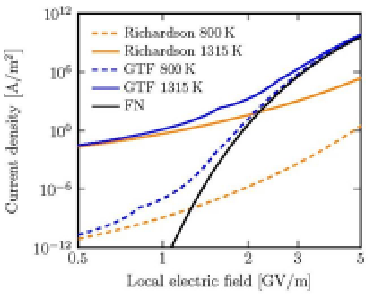
- Both Z_d and Z_w are difficult to determine precisely
- Z_d is affected by screening in a metal
- Z_w depends on the electron transport corss section
  - Difficult to calculate (Possible project coming)

N

FEM simulations and connection to KMC – University of Tartu

The emission currents

General Thermal Field model - Simulations of emission currents over large surfaces



- Thermionic emission: high temperature, low field
- Field emission: low temperature, high field
- Combined effects : general thermal field equation:

$$J_{\mathrm{GTF}}(F,T) = A_{\mathrm{RLD}} T^2 N\left(\frac{\beta_T}{\beta_F}, \beta_F(E_o - \mu)\right)$$

$$N(n,s) \approx n^2 \Sigma\left(\frac{1}{n}\right) e^{-s} + \Sigma(n) e^{-ns},$$

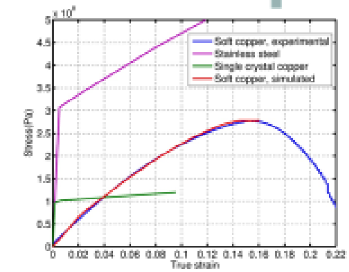
Special interest:
Intermediate region where thermal contribution can be significant

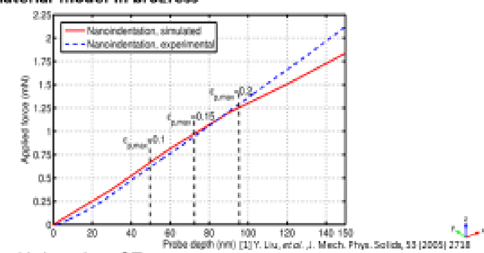
V. Zadin, University of Tartu

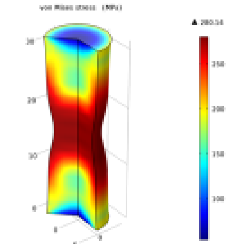
K. L. Jensen, J. Appl. Phys. (2007)

Elastoplastic deformation simulations

- Elastoplastic deformation of material, simulation of large strains
- Validation of material model and parameters by conducting tensile stress simulations
- Accurate duplication of the experimental results (tensile and nanoindentation test)
- **Parameters from tensile test are macroscopic, single crystal parameters are needed due to large grains in soft copper**
- **Incorporation of surface effects to anisotropic elastic material model in progress**

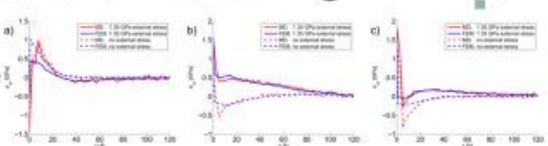


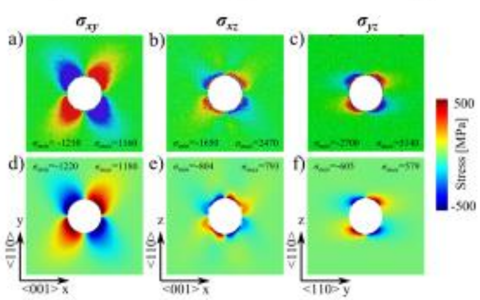




Surface stress effects in nanoscale modelling

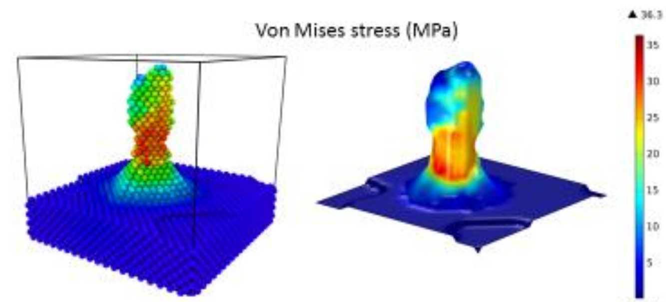
- Anisotropic material model
- Crystal plane dependent surface properties
- The surface effects important below ~ 6-10 nm
  - Corrections for surface stress (surface tension)
  - Model complexity improved towards nonlocal simulations
  - Strongest/weakest nanostructure estimation
- Plastic deformation
  - Accurate limits to be determined
  - Dependence from grain size, average dislocation length and plastic deformation activation volume
  - More complex model needed to account microstructure effects, dislocation densities etc.





V. Zadin, University of Tartu *MeVArc 2015*

Simulation outputs

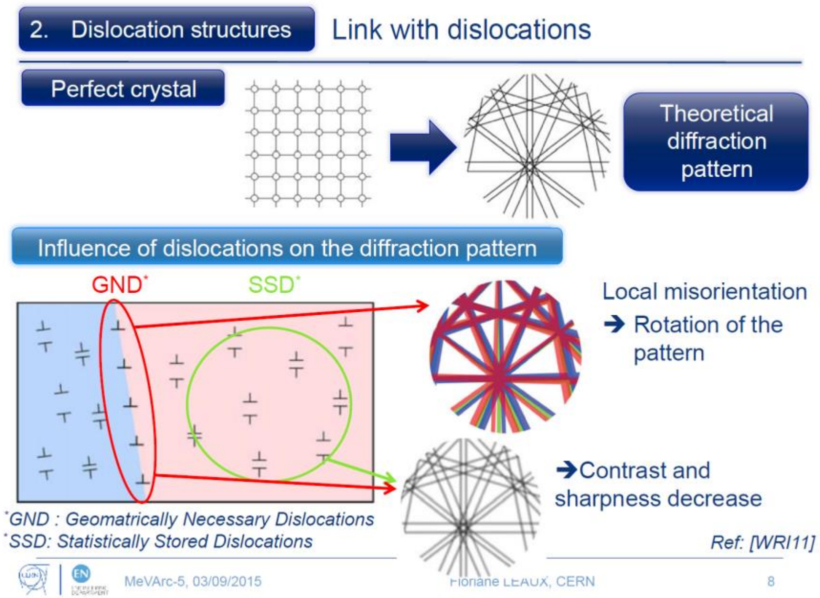


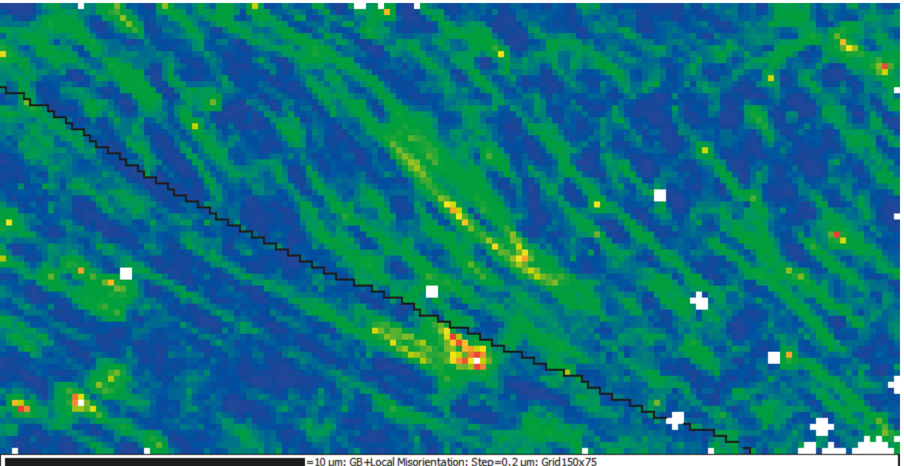
The Good:
- Robust surface detection – all geometries and surfaces can be handled
- All our existing FEM models can be used

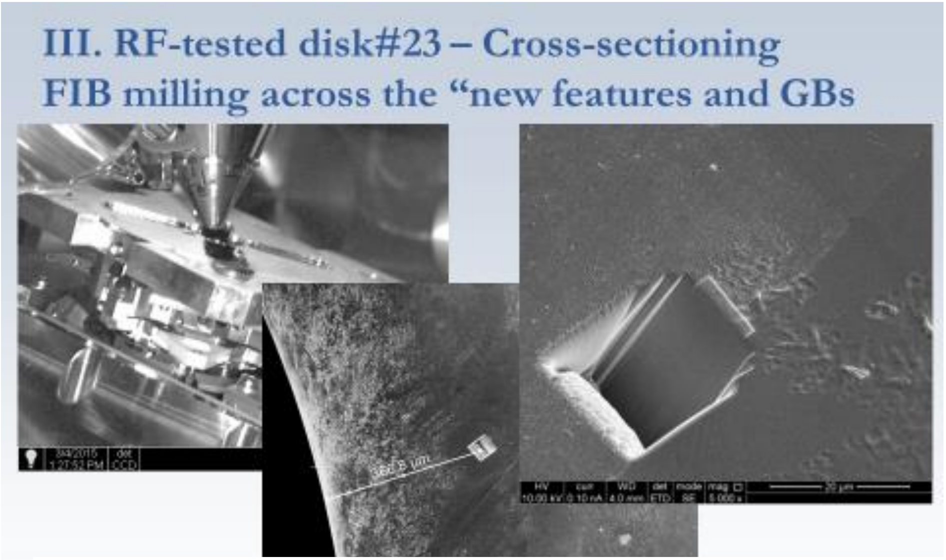
The Bad:
- Influence of adatoms needs better handling
- Emission currents from ultra small areas – single atom can emitter most of the current
- Speed optimization needed!

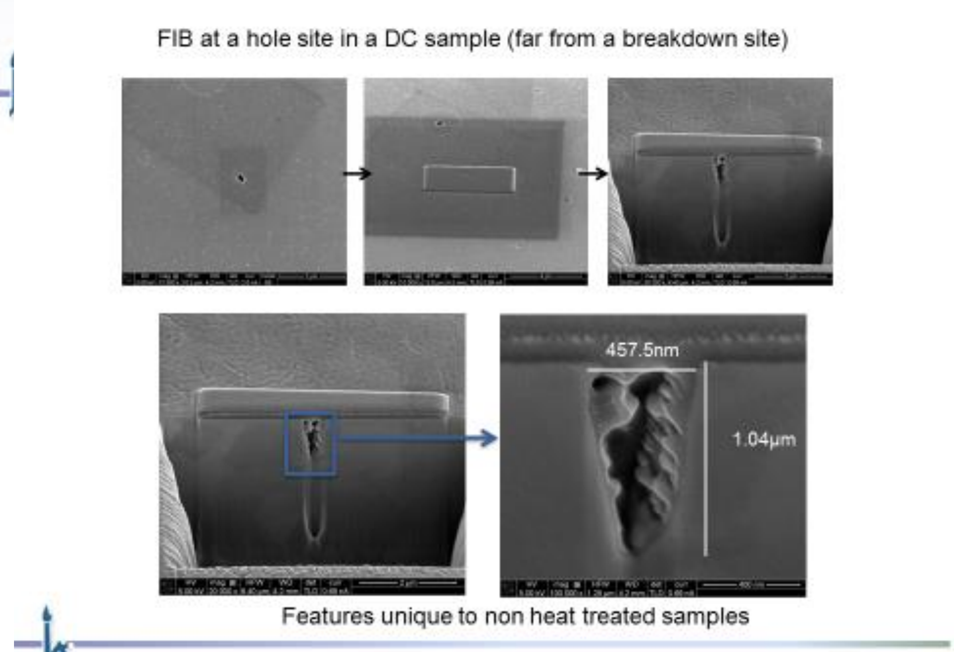
V. Zadin, University of Tartu *MeVArc 2015*

Advanced microscopy – Hebrew University of Jerusalem and CERN



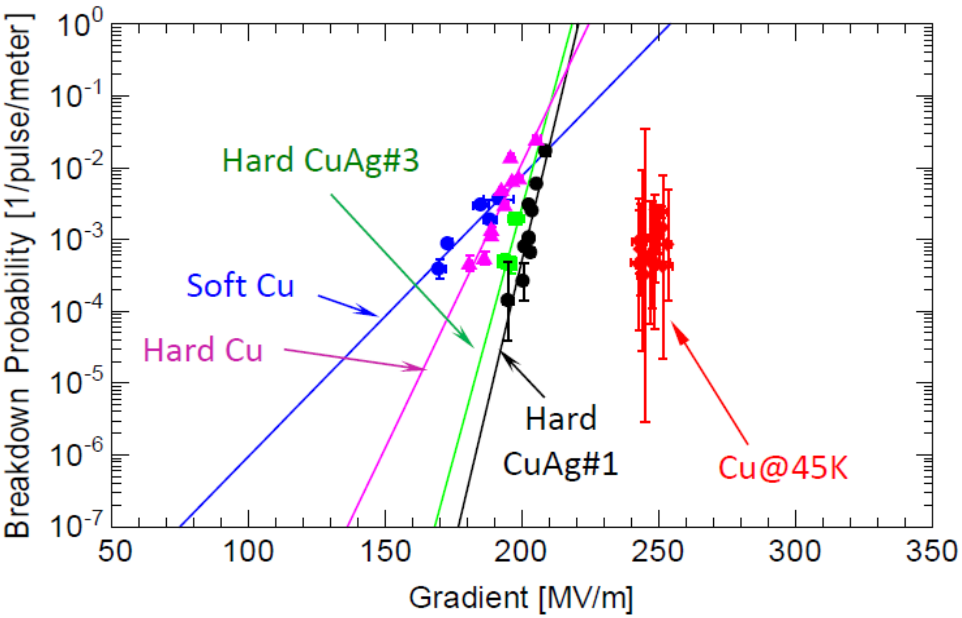


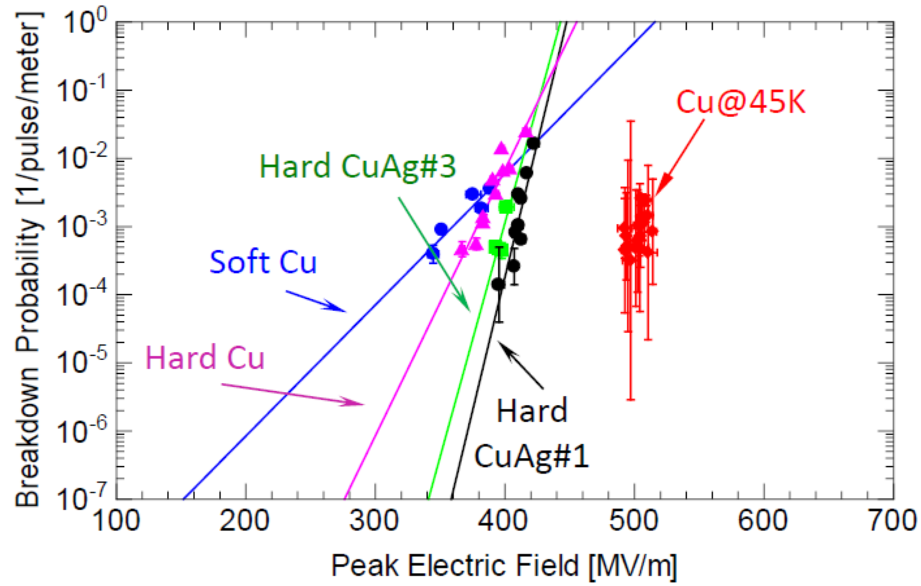




V. Dolgashev, EAAC2015
https://agenda.infn.it/contributionDisplay.py?contribId=227&confId=8146

RF breakdown performance of normal conducting cryo structure at 45 deg. K assuming Qo from fitting of the power signals, *first breakdowns*





For the breakdown probability 10^{-3} .. 10^{-4} 1/pulse/m cryo structure clearly outperforms record data from hard CuAg obtained in initial stages of conditioning. CuAg on final stages of conditioning very similar to hard Cu.

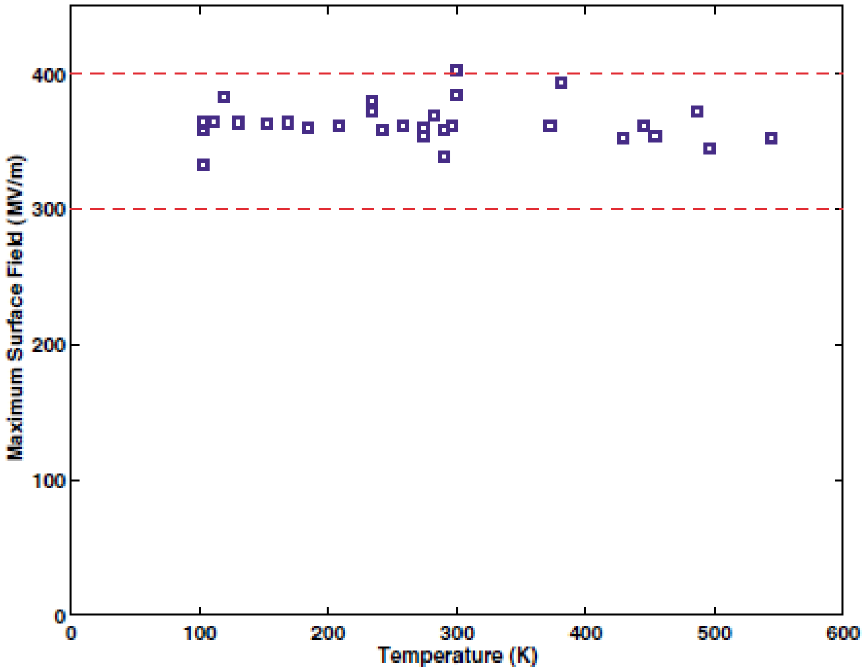


FIG. 6 (color online). Temperature dependence of maximum surface field.

Frequency and Temperature Dependence of Electrical Breakdown at 21, 30, and 39 GHz

H. H. Braun, S. Döbert, I. Wilson, and W. Wuensch*

European Organization for Nuclear Research (CERN), CH 1211 Geneva 23, Switzerland

(Received 1 July 2002; published 5 June 2003)

A TeV-range e^+e^- linear collider has emerged as one of the most promising candidates to extend the high energy frontier of experimental elementary particle physics. A high accelerating gradient for such a collider is desirable to limit its overall length. Accelerating gradient is mainly limited by electrical breakdown, and it has been generally assumed that this limit increases with increasing frequency for normal-conducting accelerating structures. Since the choice of frequency has a profound influence on the design of a linear collider, the frequency dependence of breakdown has been measured using six exactly scaled single-cell cavities at 21, 30, and 39 GHz. The influence of temperature on breakdown behavior was also investigated. The maximum obtainable surface fields were found to be in the range of 300 to 400 MV/m for copper, with no significant dependence on either frequency or temperature.

DOI: 10.1103/PhysRevLett.90.224801 PACS numbers: 29.17.+w, 41.75.Lx, 52.80.Pi, 52.80.Vp

We didn't measure breakdown rate and quote "maximum." From memory was probably around 10^{-2}

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

$$E^f = 0.8\ eV$$

$$\Delta V = 0.8 \times 10^{-24} m^3$$

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 15, 071002 (2012)

Defect model for the dependence of breakdown rate on external electric fields

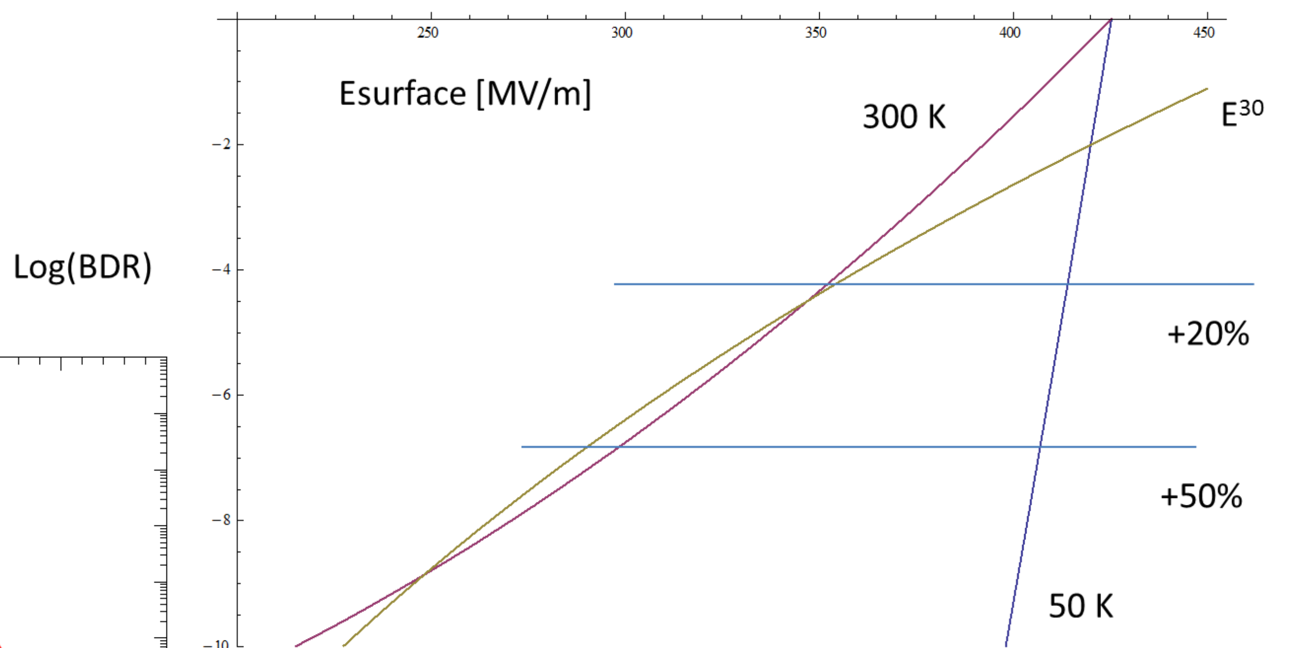
K. Nordlund and F. Djurabekova

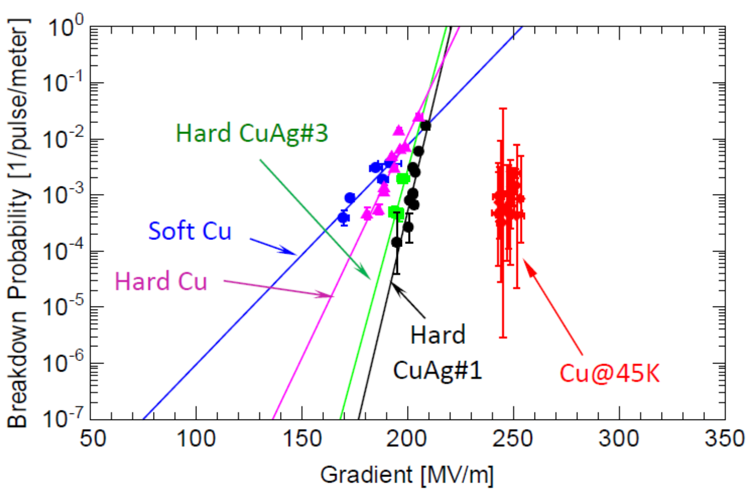
Helsinki Institute of Physics and Department of Physics, University of Helsinki, P.O. Box 43, FIN-00014, Helsinki, Finland

(Received 1 August 2011; revised manuscript received 2 April 2012; published 11 July 2012)

We develop an analytical model for the vacuum electric breakdown rate dependence on an external electric field, observed in test components for the compact linear collider concept. The model is based on a thermodynamic consideration of the effect of an external electric field on the formation enthalpy of defects. Although strictly speaking only valid for electric fields, the model also reproduces very well the breakdown rate of a wide range of radio-frequency breakdown experimental data. We further show that the fitting parameter in the model can be interpreted to be the relaxation volume of dislocation loops in materials. The values obtained for the volume are consistent with dislocation loops with radii of a few tens of nanometers.

DOI: 10.1103/PhysRevSTAB.15.071002 PACS numbers: 52.80.Vp, 61.72.Lk, 29.20.Ej, 52.80.Mg





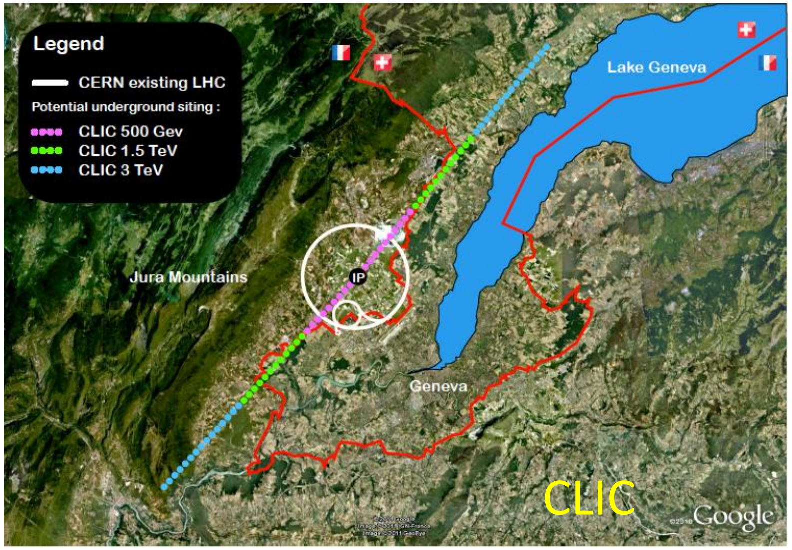
Walter Wuensch, CERN

Applications

Selected high-gradient ncrf applications

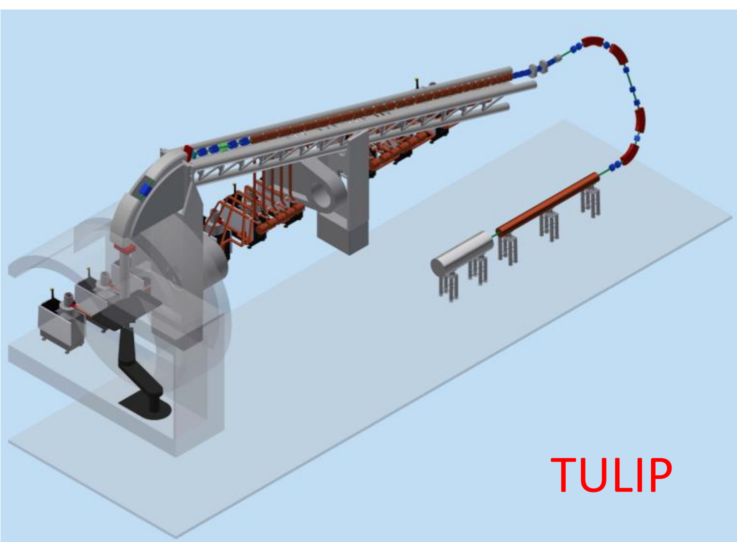
- Linear Colliders – High-energy physics facility
- XFELs – User facilities for material science, biology, chemistry, etc.
- Compton-scattering sources – Laboratory to room-sized X-ray sources, user facility
- Medical – compact linacs for proton and carbon ion cancer treatment
- Sub-system – energy spread linearizer, deflecting cavity

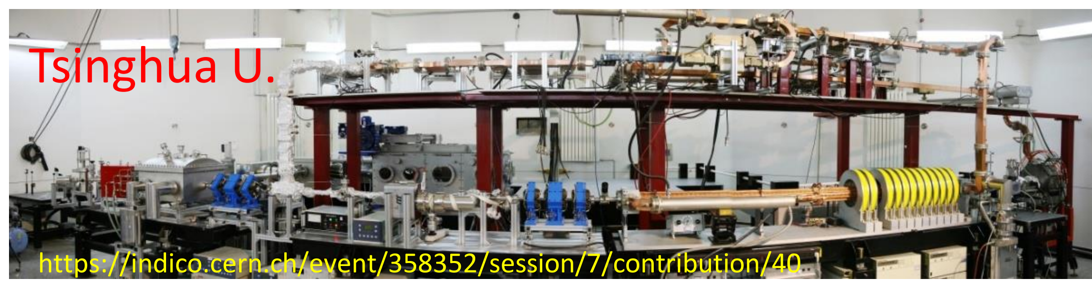
Scale of applications



Linear collider

XFEL





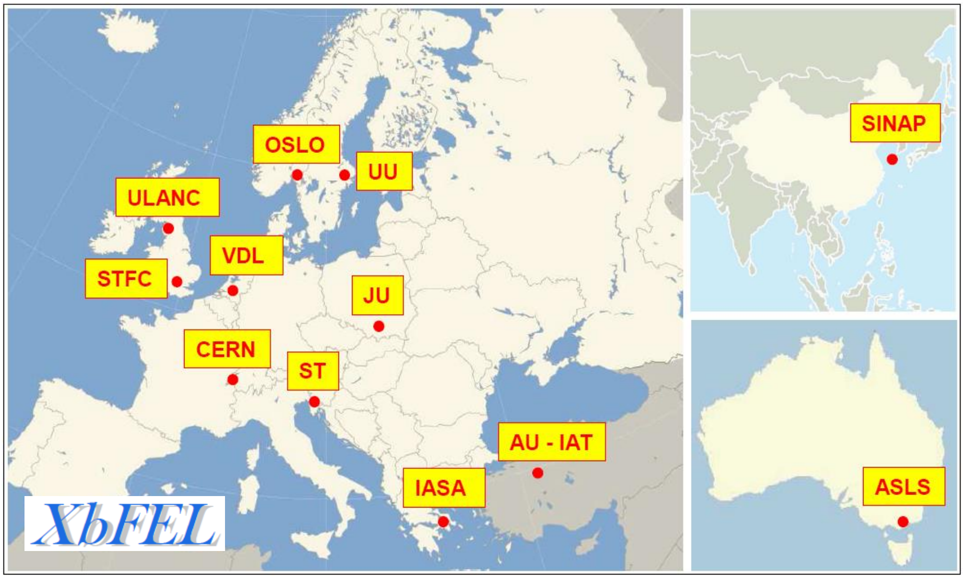
Proton therapy

Thompson/Compton source

The XbFEL Collaboration

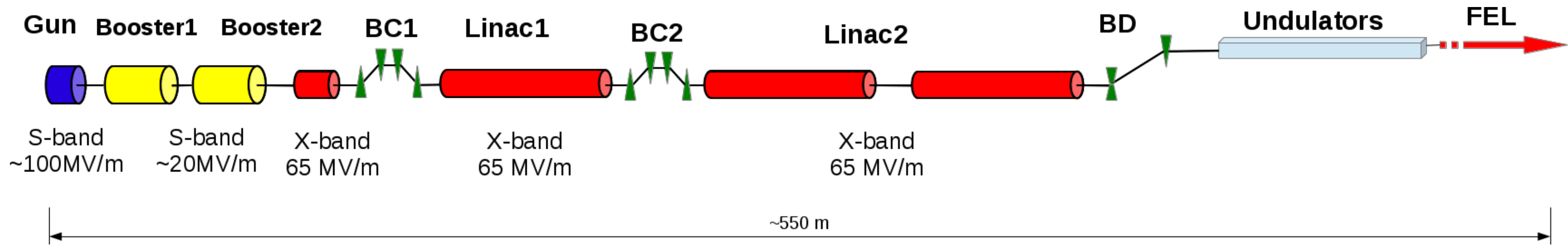
The aim of the XbFEL Collaboration is to promote the use of X-band technology for FEL based photon sources.

http://xbandfel.web.cern.ch/



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.*

Proposed Layout



It consist of:

- **RF photocathode gun** → S band structure delivering beam @7 MeV with 250 pC charge, 2.5 ps (800µm) lengt and 0.25 mm rad emittance
- **Injector** → S-band structures and one X-band structure as linearizer, accelerating beam up to 300 MeV
- **Two main linacs** → Two X-band modules: stage one 0.3 GeV → 2.0 GeV
  stage two 2.0 GeV → 6.0 GeV
- **Two bunch compressors , Beam delivery lines , Undulator(s), Laser transport line(s)**

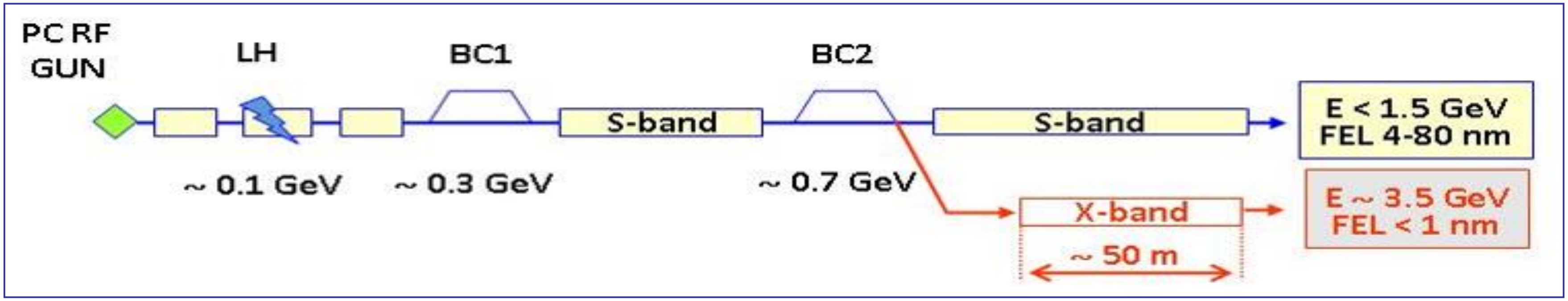
The advantage of using X-band:

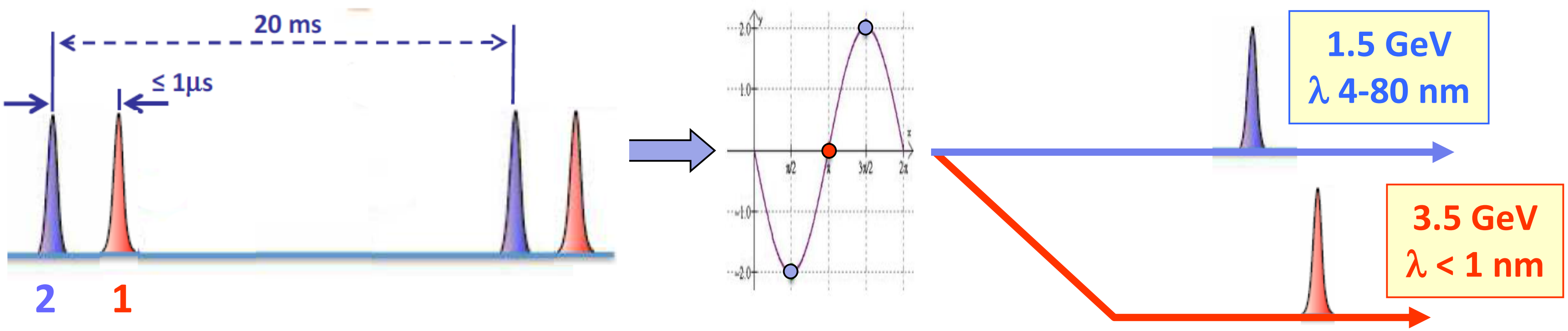
- Compact reduction of length with high gradient
- Costs reduction
- Possibility to go to a high repetition rate (up to kHz regime)

Turkish project

Courtesy of A. Aksoy

FERMI perspectives





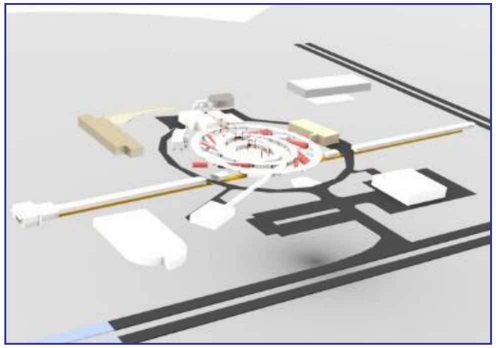
S-band linac
two e-bunches/RF pulse

HF bunch separator

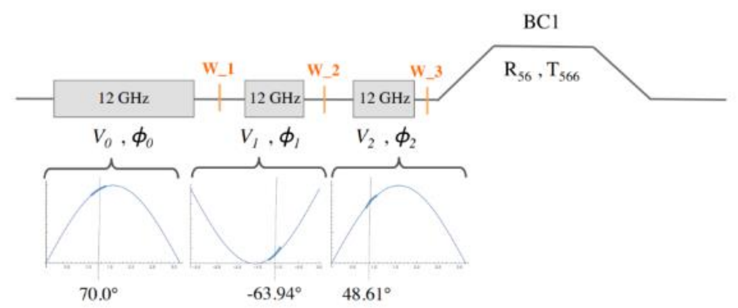
Two separate linacs at 50 Hz
S-band → 1.5 GeV
X-band → 3.5 GeV

X-Band Activities in Australia

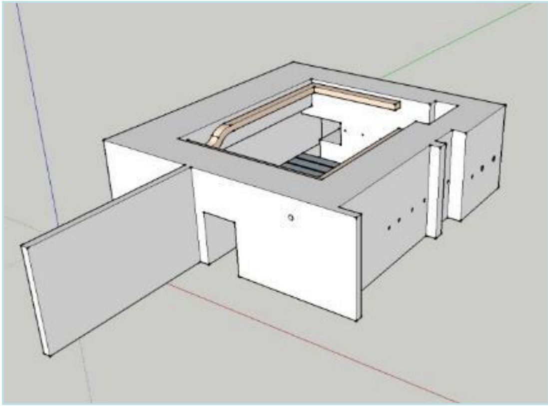
- Part of the XbFEL Collaboration spun out from CLIC, planning XbFEL as an upgrade path for the Australian Synchrotron light source.
- Modelling all XbFEL linac with novel linearlisation scheme.
- Propose an "XBOX3" type test stand at the University of Melbourne.



Concept drawing of AXXS Australian X-Band X-Ray Source. (M. Boland)



Phase Modulation Linerisation in an all X-band Linac (T. Charles *et. al.* , Proceedings of IPAC 2015)



Bunker for former 35 MeV betatron at the University of Melbourne. (M. Boland)

Courtesy of M. Boland

Shanghai Photon Science Center at SINAP

SXFEL: Shanghai Soft X-ray FEL

S-band, C-band, X-band

Energy: 0.84GeV (Phase I),

1.3GeV (Phase II)

Compact hard X-ray FEL (X-band, S-band)

Energy: 6.5GeV, 8GeV (200m linac)

Total length: About 550 meters

SSRF: Shanghai Synchrotron Radiation Facility

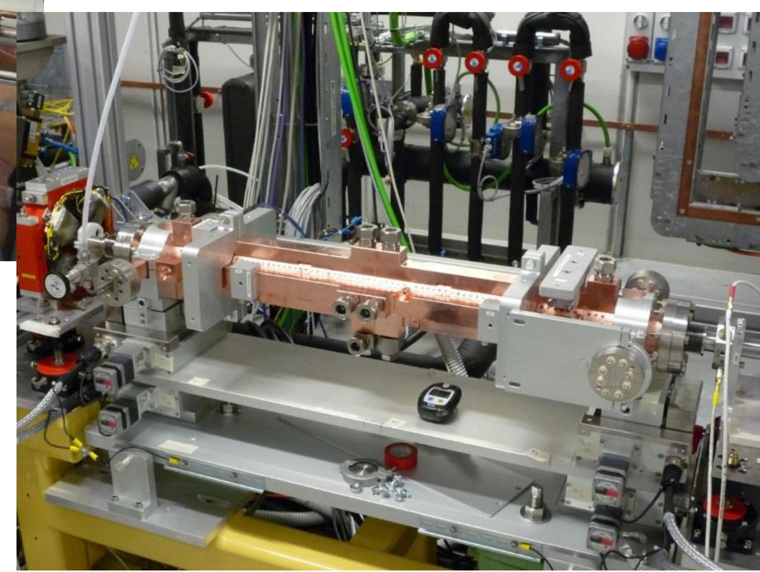
Energy: 3.5GeV, user operation

Courtesy of W

Energy spread linearizer FERMI@Elettra

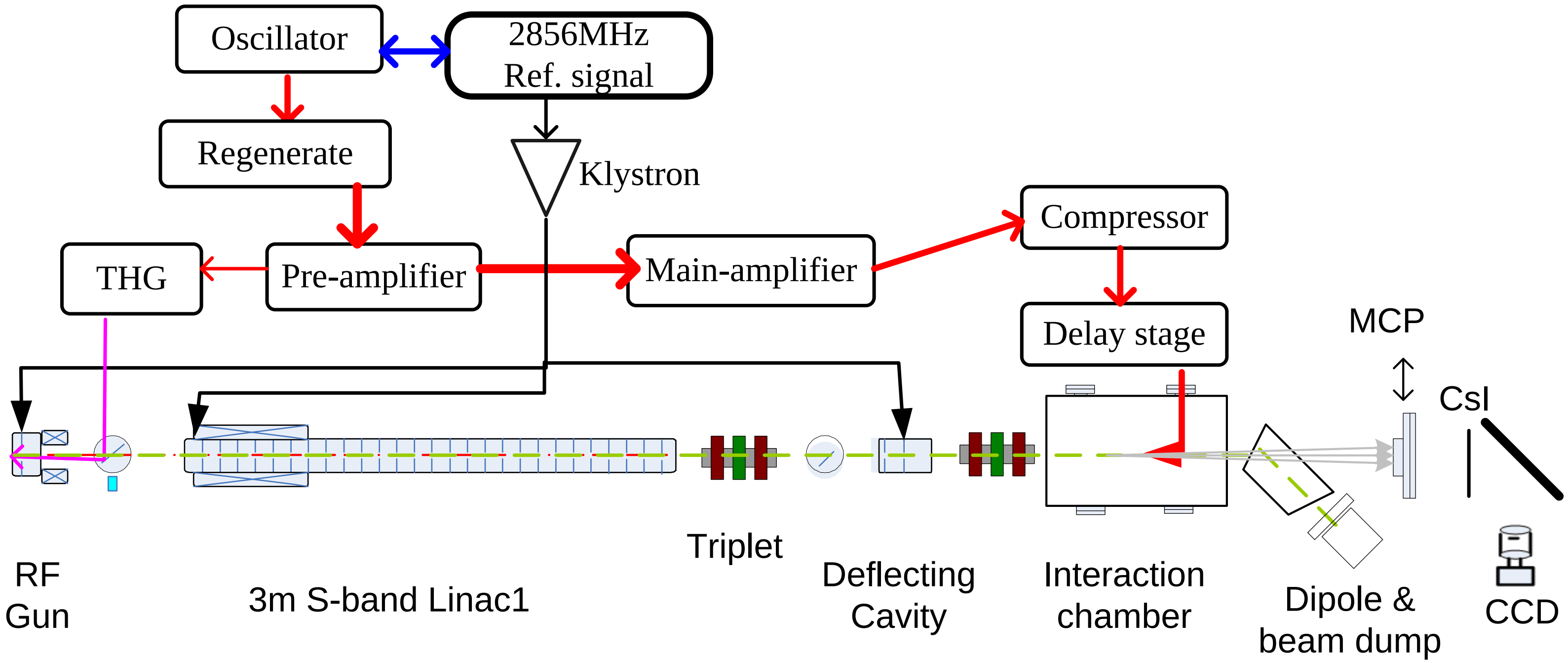
Routine operation of X-band system for energy spread linearization at FERMI@Elettra based on SLAC XL-5 klystron. Same system installed at PSI.

G. D'Auria



Deflectors for longitudinal bunch profile measurements are another big area.

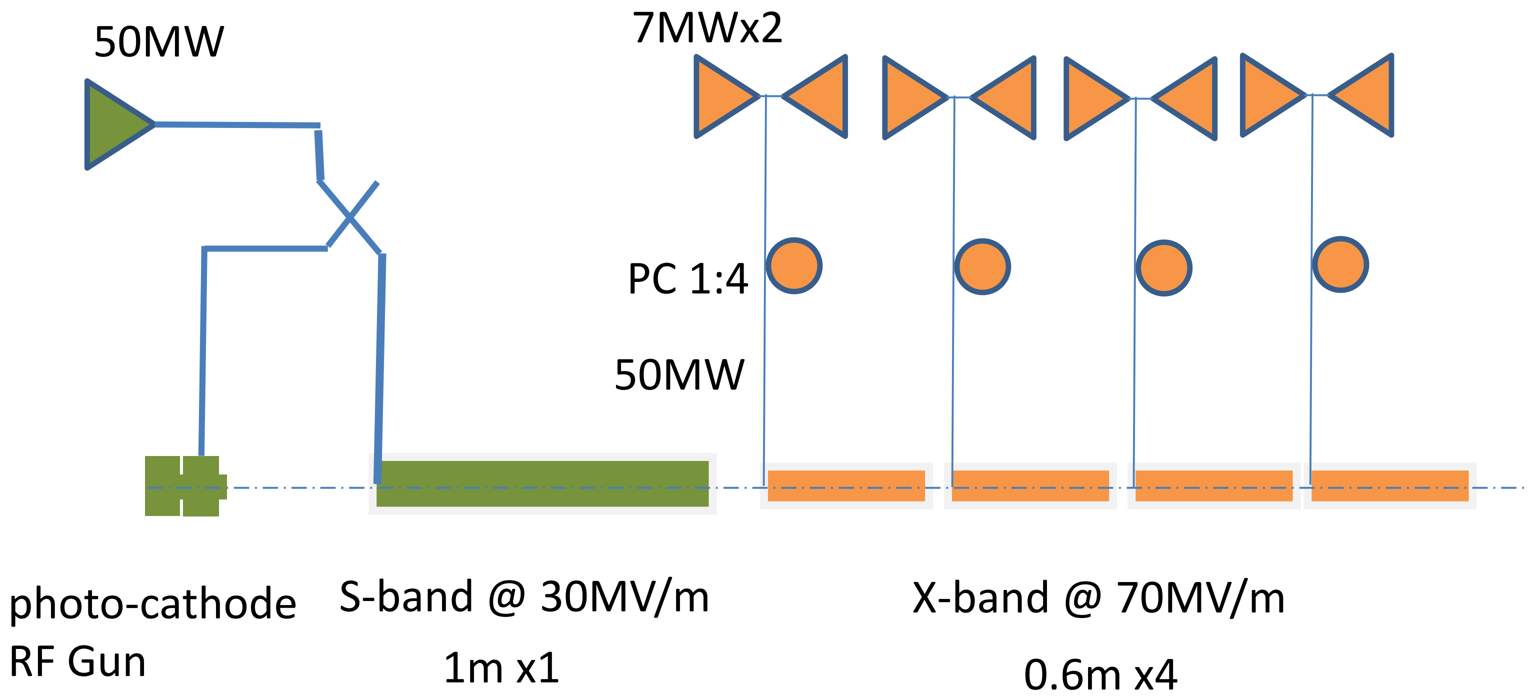
Tsinghua Thomson scattering X-ray source (TTX)



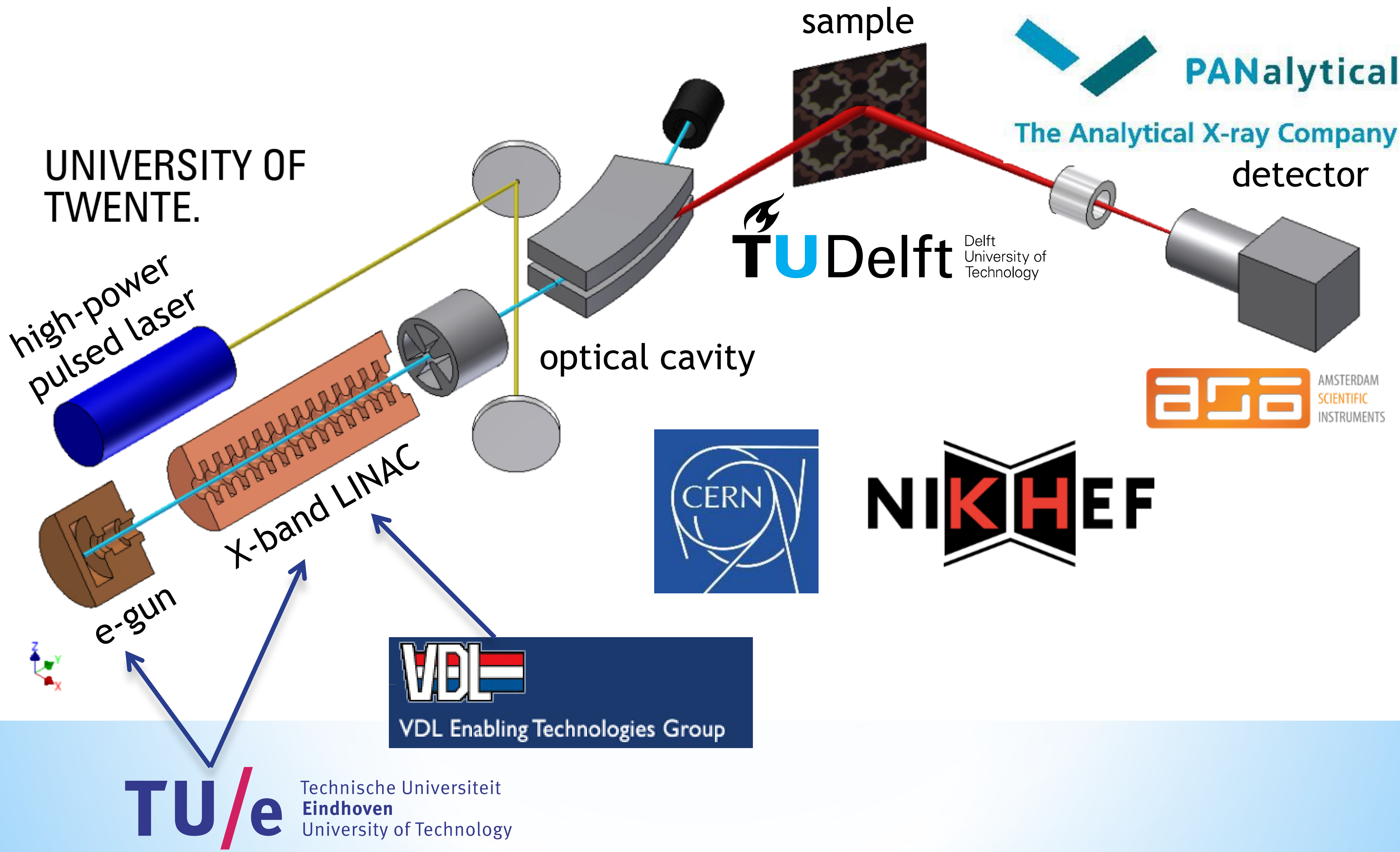
Electron beam		Laser beam	
Energy	45MeV	Wavelength	800nm
Bunch length	1~4ps	Pulse duration	~30fs
Charge	~0.7nC	Pulse energy	~500mJ
Beam size	30x25um	Beam size	~30um

Parameters of Scattering X-ray	
Photon energy	24(90deg)~48(180deg)kev
Pulse duration	0.16(90deg)~3(180deg)ps
Number photons	$8.4X10^6$(90deg)~$5.5X10^7$(180deg)

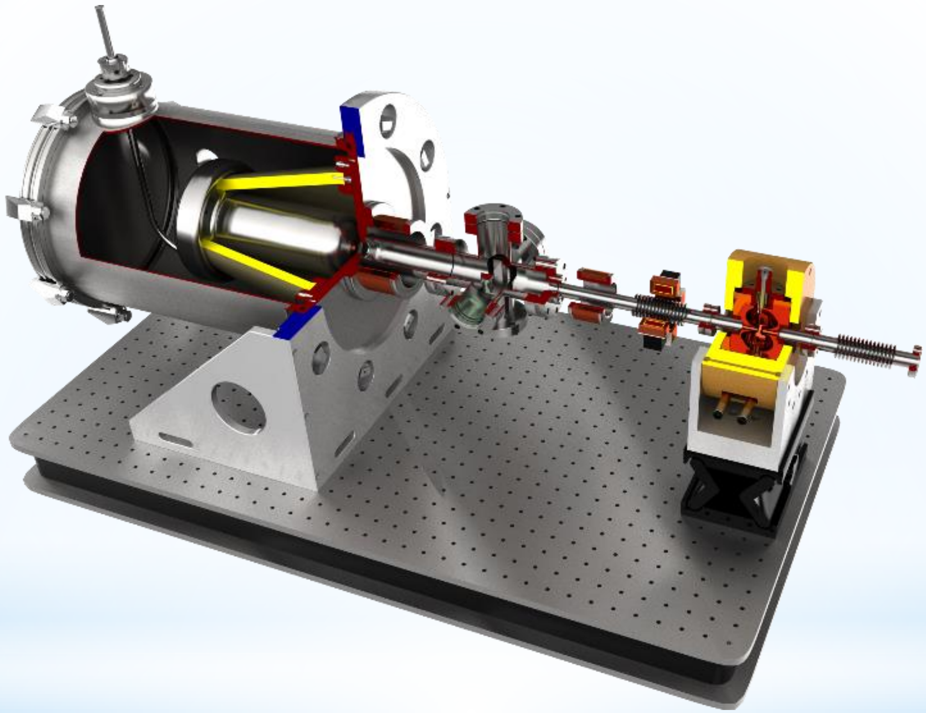
200MeV linac layout (Preliminary design)



Compton Back Scattering source

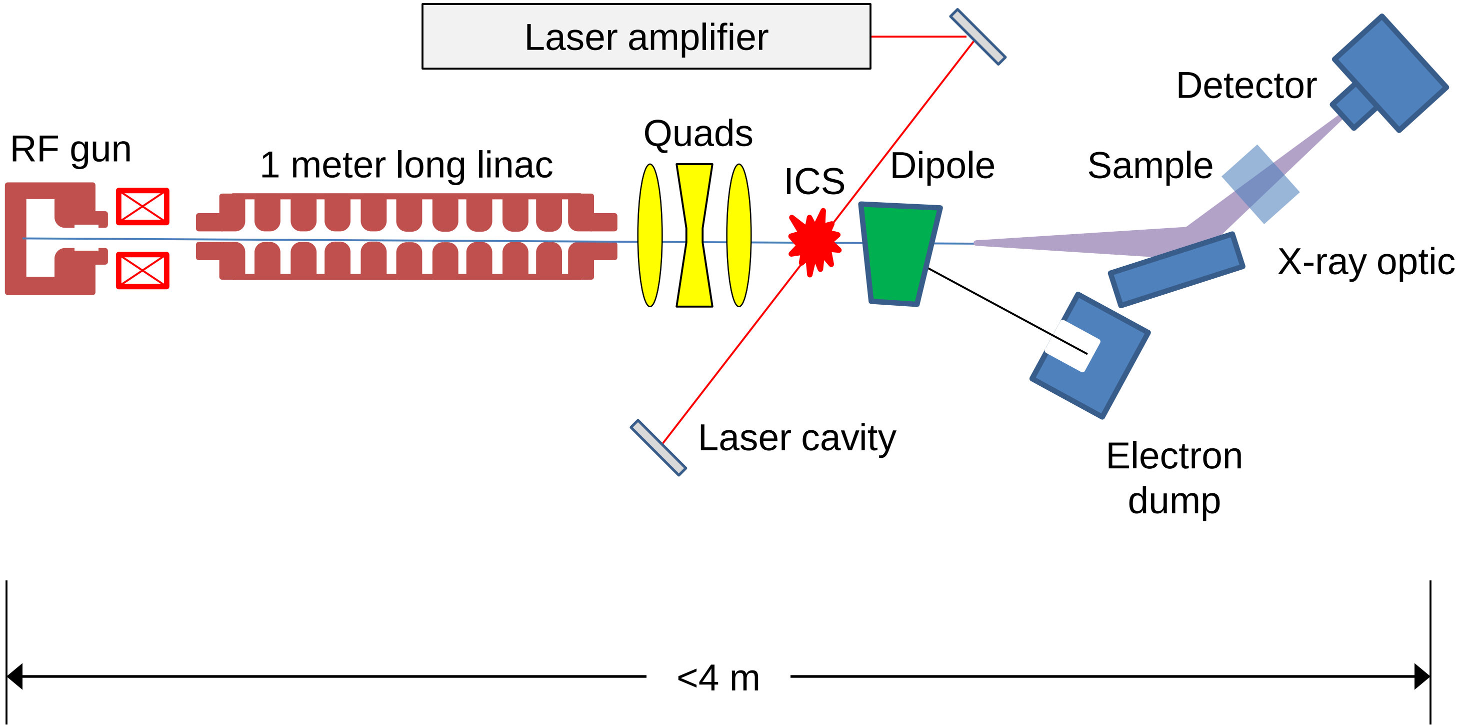


Low-emittance pulsed electron gun

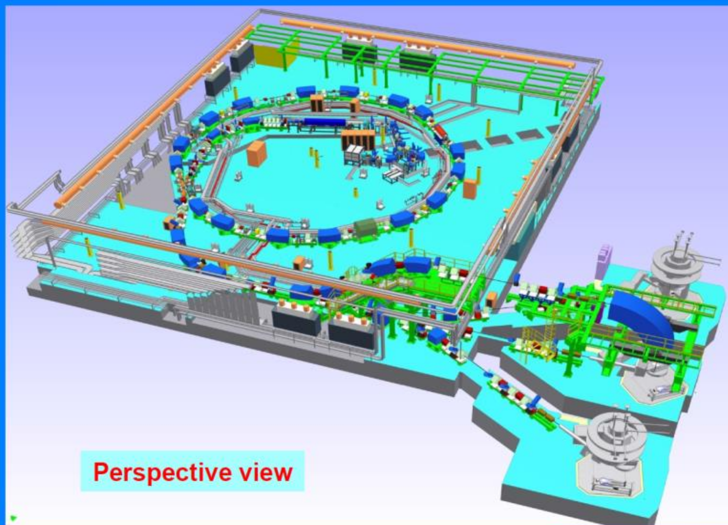


- 100 keV DC electron gun;
- pulsed operation by femtosecond laser photoemission;
- 1 pC bunches @ 40 nm rad normalized emittance;
- 10 pC bunches @ 120 nm rad normalized emittance;
- developed @ TU/e, sold through AccTec BV;
- currently under development: pulsed CeB_6 thermionic operation.

Basic Layout for ICS



CNAO at Pavia



MedAustron is being completed in Wiener Neustadt

MedAustron bought from CNAO Foundation the construction drawings for 4 million Euro (agreement with CERN-CNAO-INFN)

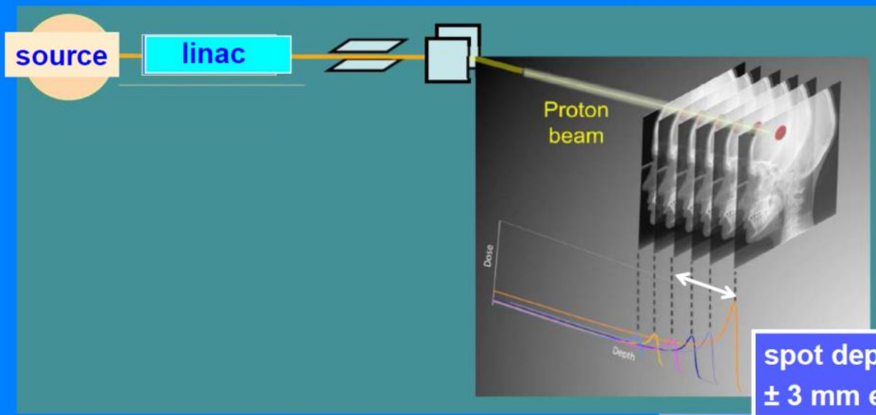
CNAO = Centro Nazionale di Adroterapia Oncologica

MedAustron participated in PIMMS

Protons have been sent to treatment room

With linacs the dose deposition depth can be adjusted every 3 ms

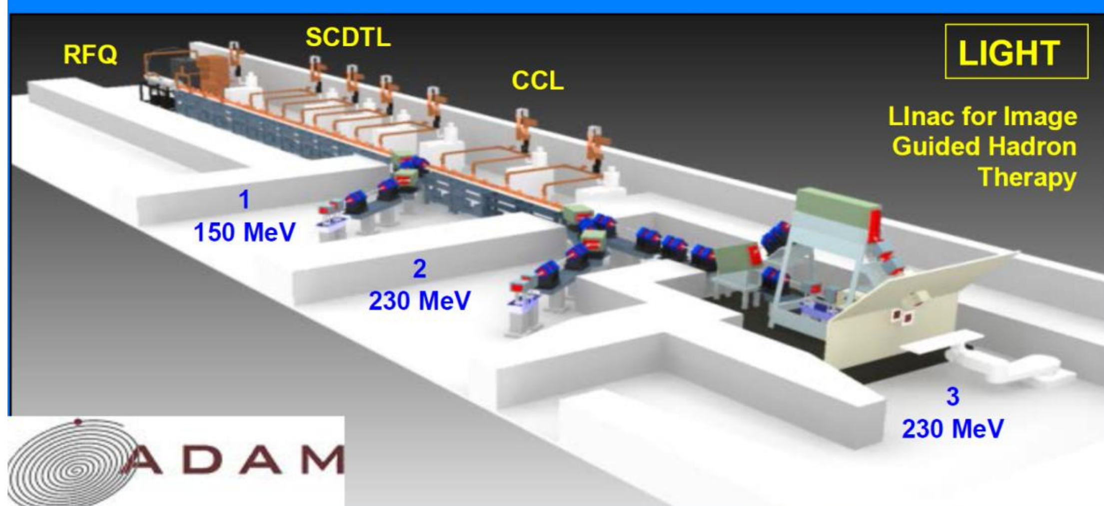
linac pulses: 200 - 400 times per second



spot depth:
± 3 mm every pulse

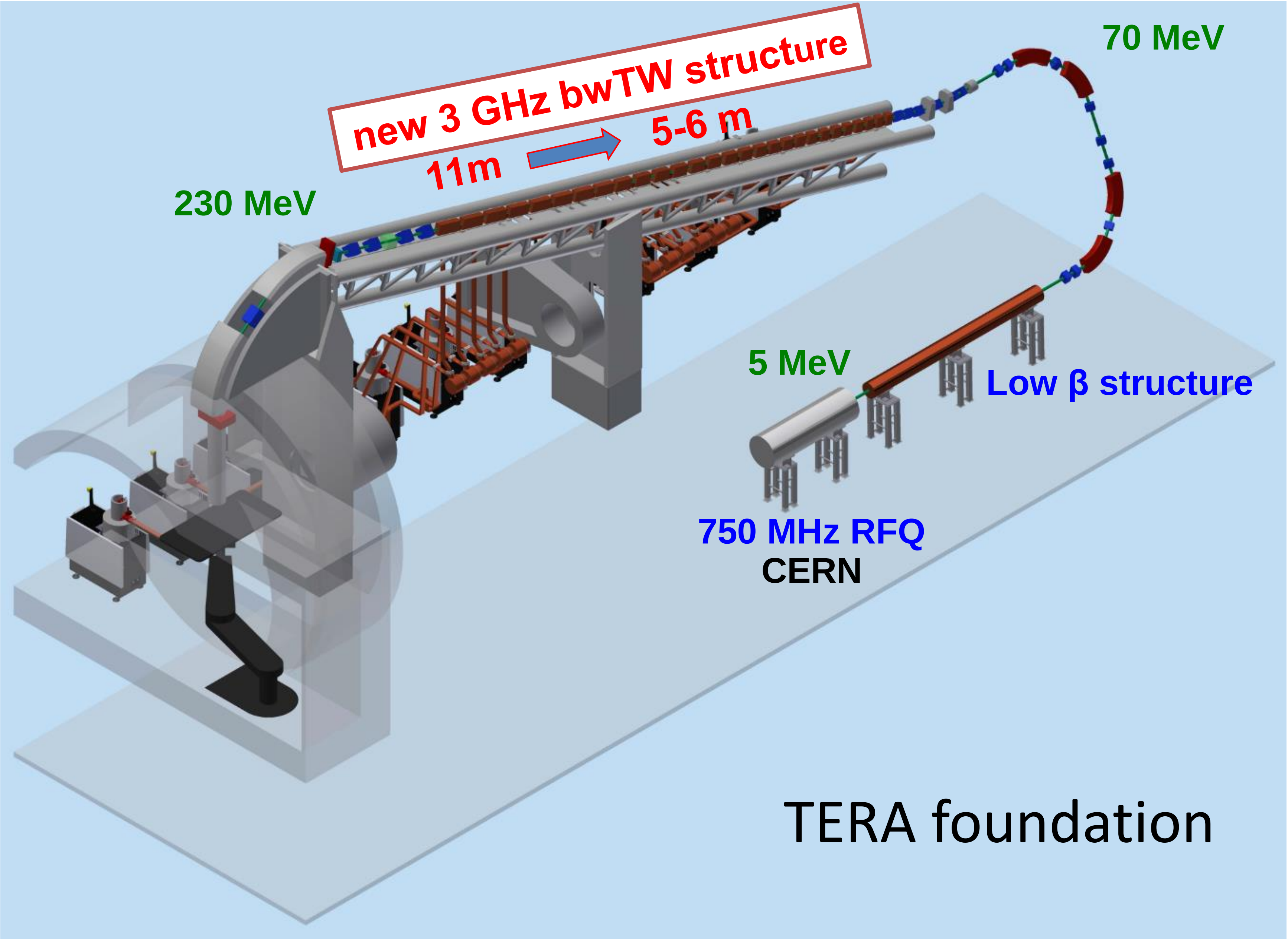
To follow moving organs in 4D - with spot scanning, motion feedback and more than 10 paintings - the beam time structure of linacs is better than the ones of cyclotrons and synchrotrons

Centre offered by A.D.A.M. – a CERN spin-off Company

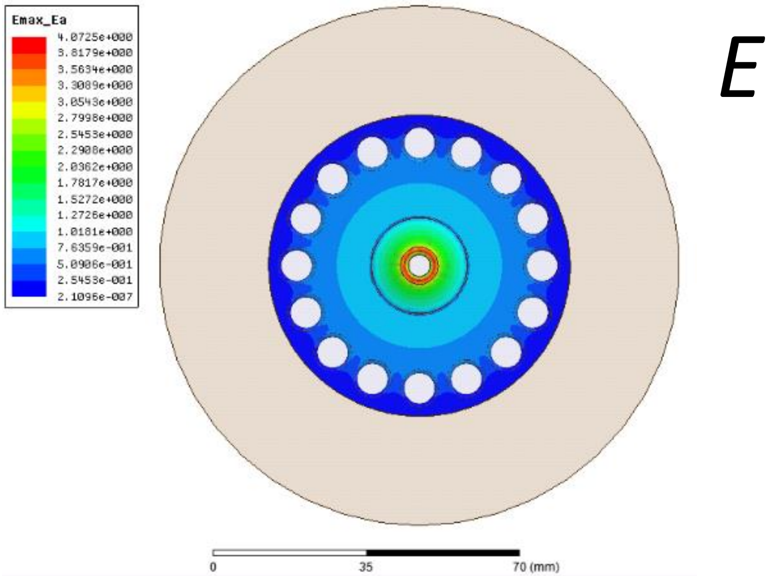


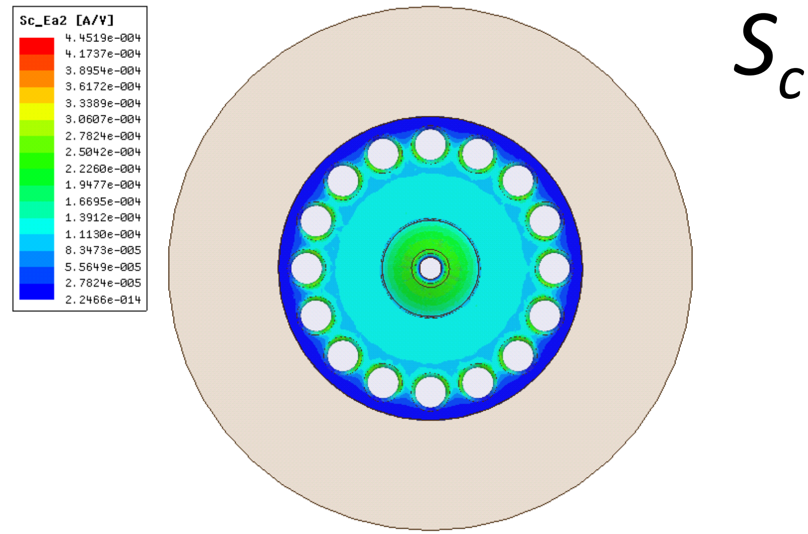
MeVArc 2015, 2 September 2015

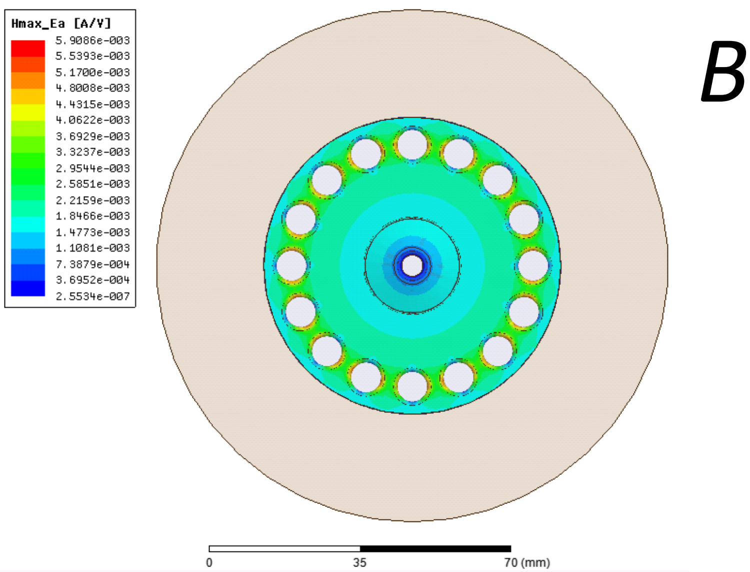
The TULIP Project



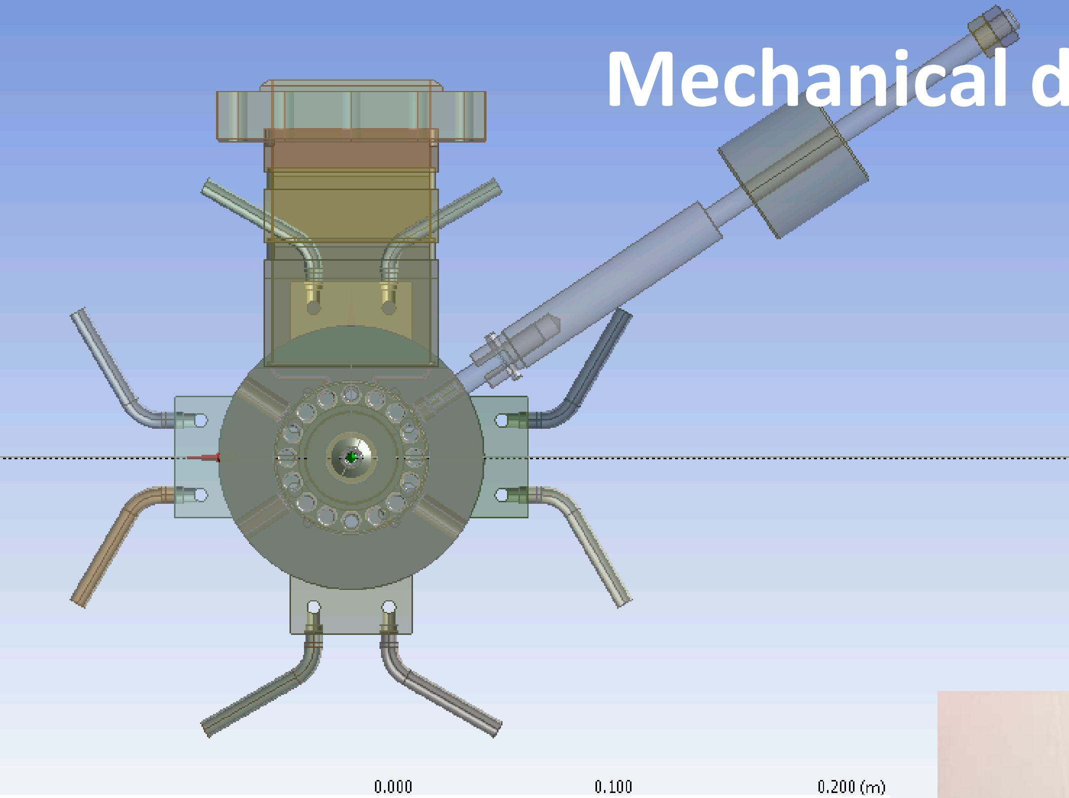
RF design and diamond machined disk

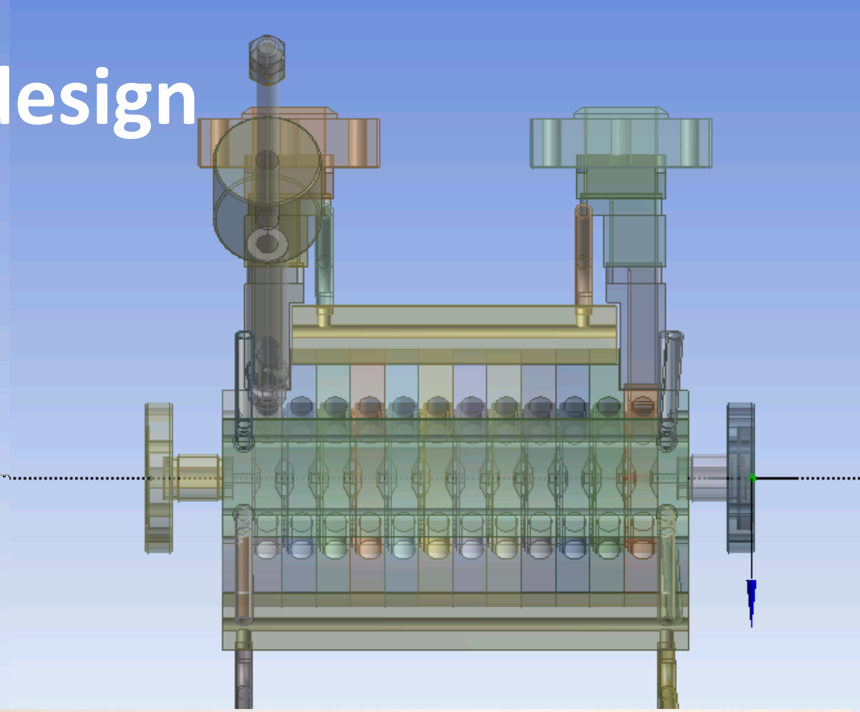


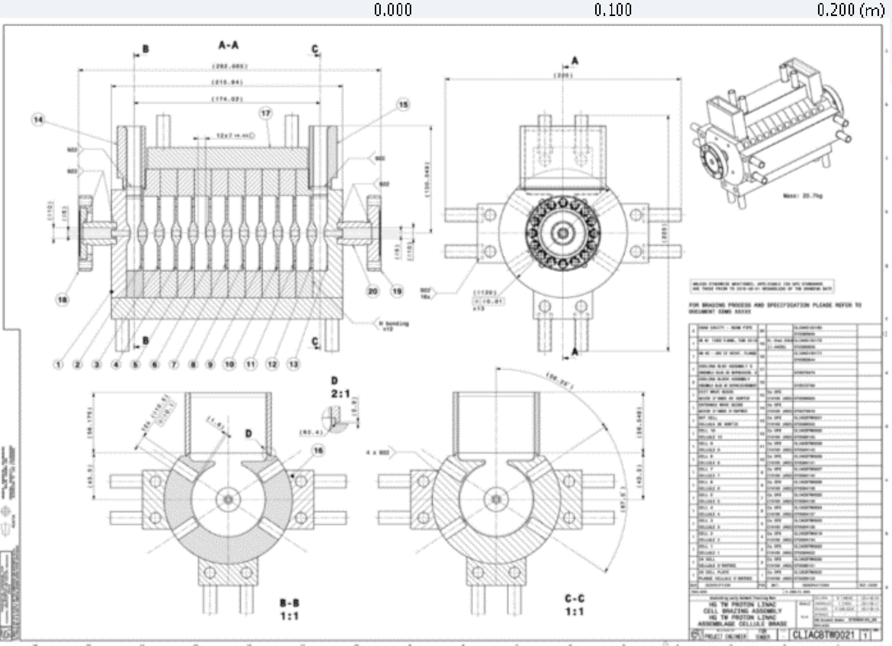


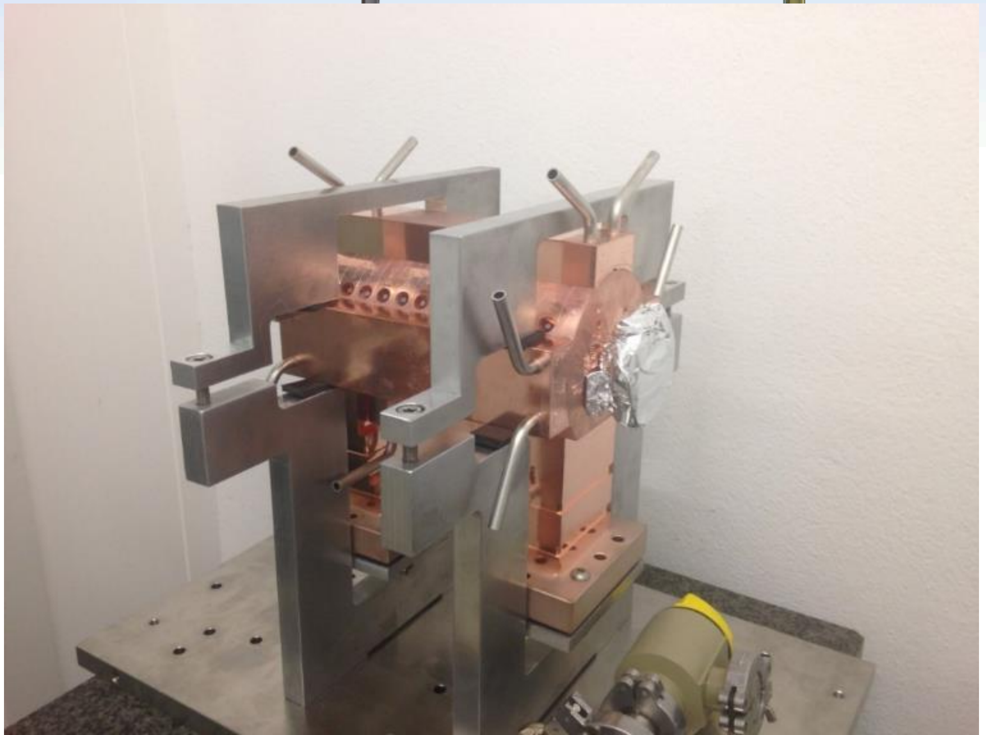


Mechanical design









X-band and high-gradient rf community

Our high-gradient and X-band applications community recently held a workshop in Beijing: https://indico.cern.ch/event/358352/.

Fundamental studies of high fields

And a workshop dedicated to vacuum arcs https://indico.cern.ch/event/354854/.

Conclusions

The field of high-gradient and high-frequency rf is in a phase of rapid development.

It is benefiting from a confluence of a number of trends: 3-D simulation, precision 3-D machining, power sources, material science, etc.

We understand high-gradient phenomena rather well now and this is resulting in robust optimized designs with still some 10's% increase in gradient in the pipeline.

Significant improvements in cost should be possible.

The potential applications range from very large to rather small scale facilities. We hope to see a few take off in the coming years.

Thank you for your attention!