Introduction to CLIC
and
X-band and High-Gradient R&D

OIST, 5 March 2015

Walter Wuensch, CERN

Outline

- Introduction to the CLIC project and collaboration: goals and status.

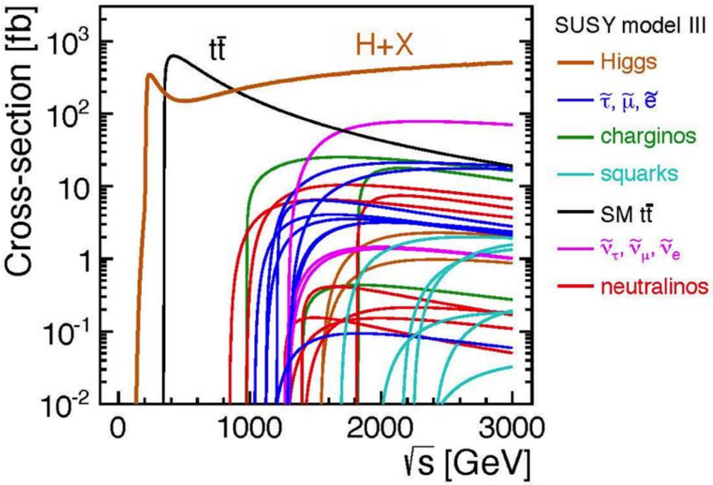
Then more on two specific development activities:

- X-band rf system development
- High-surface field studies

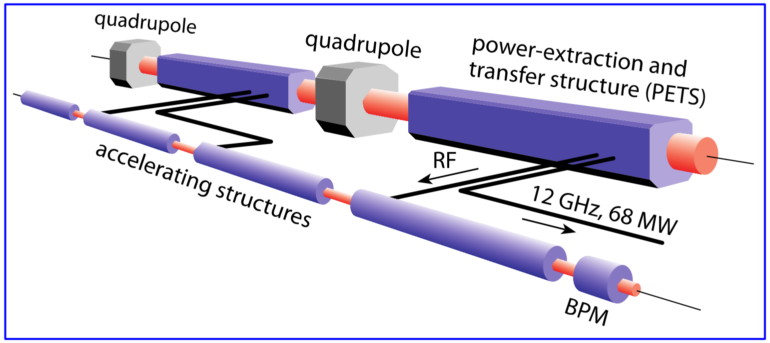
I will cover many subjects quickly to give you an overview. I am delighted to discuss with you specific subjects in greater detail.

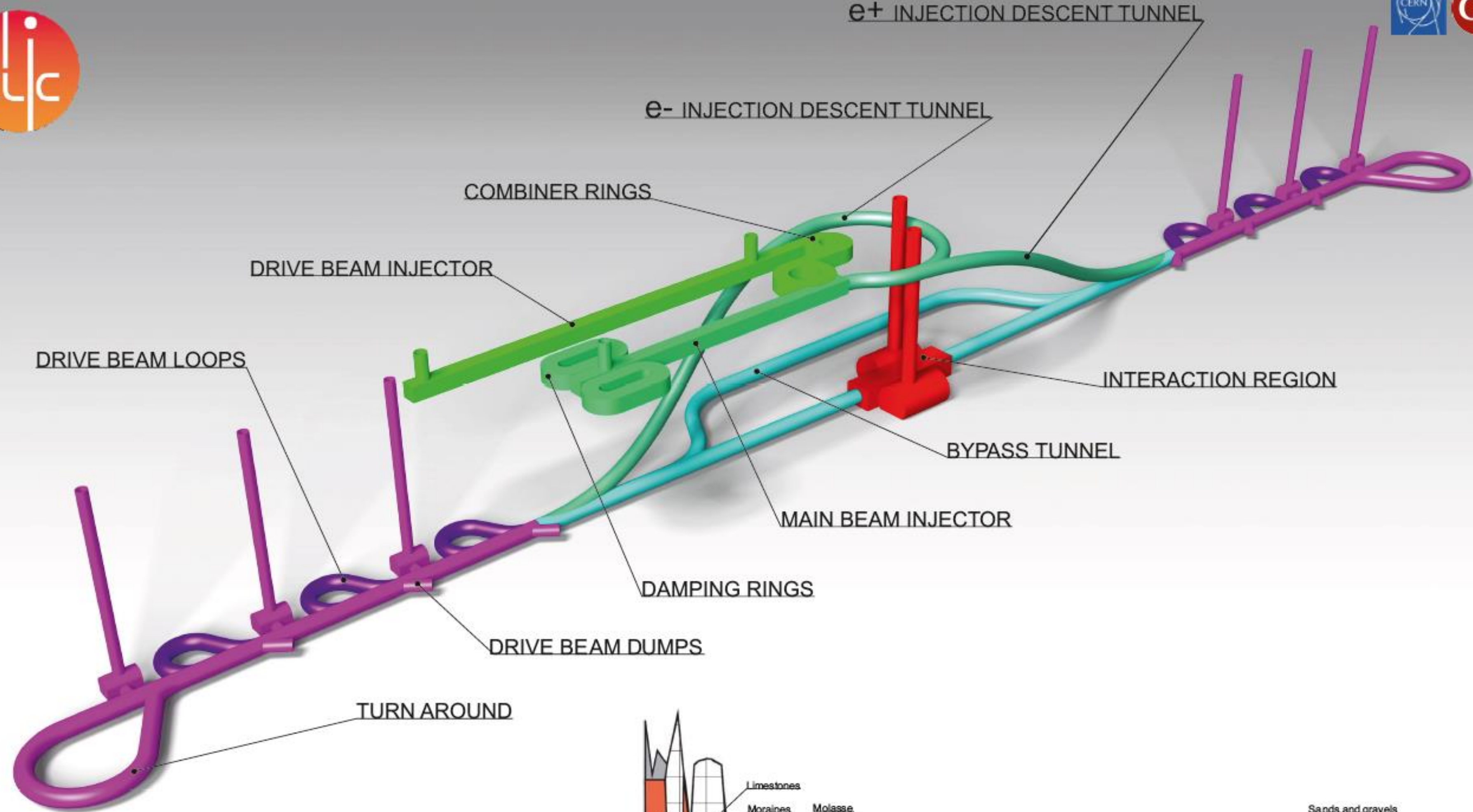
Introduction

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



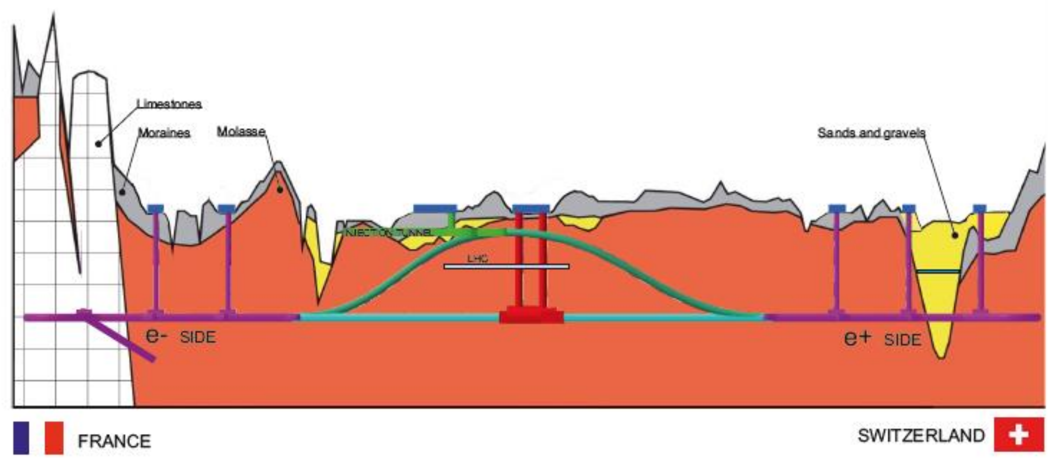
It is based on high-gradient,
100 MV/m,
normal conducting rf
and a two-beam power generation scheme



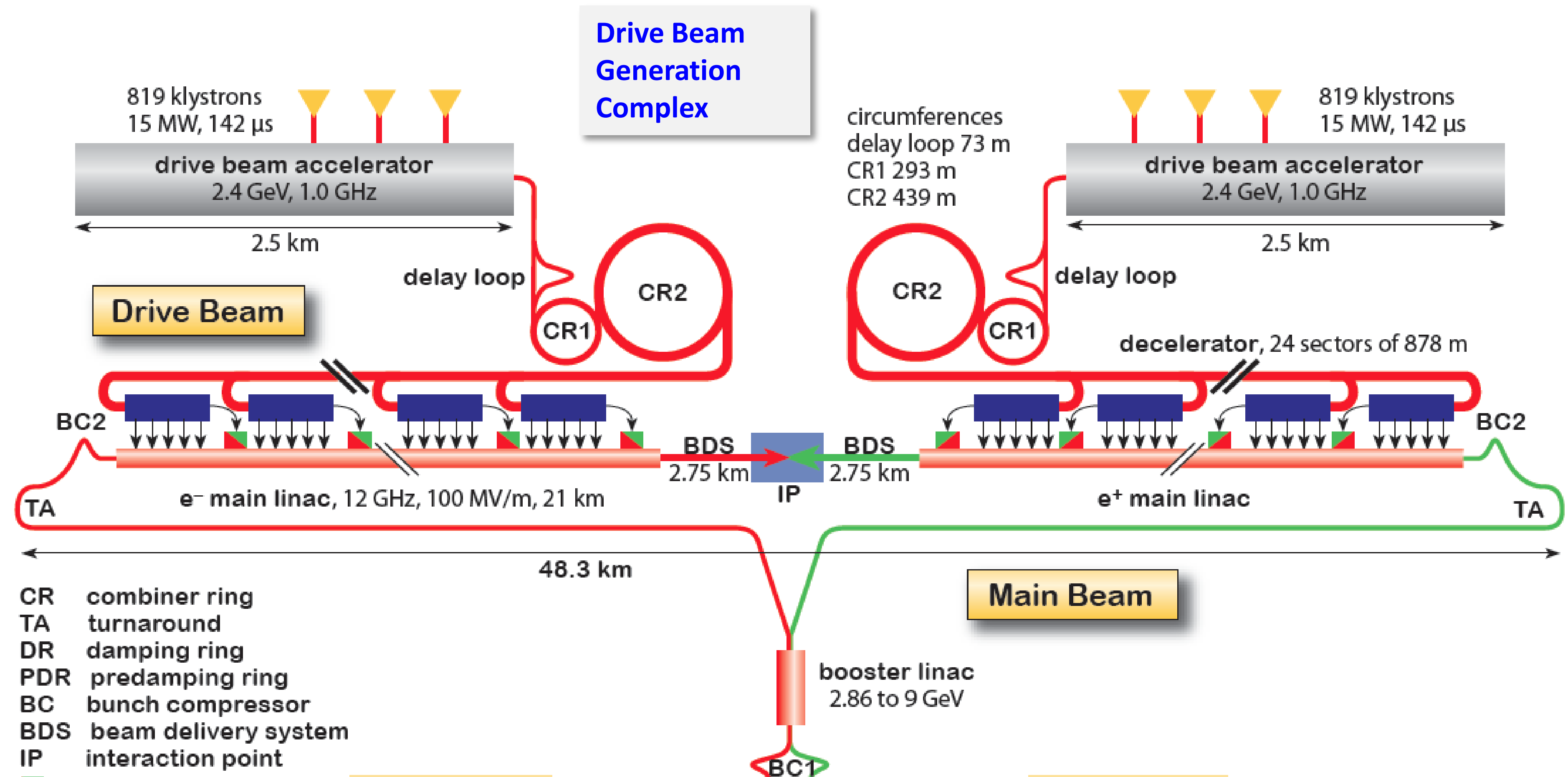


CLIC SCHEMATIC

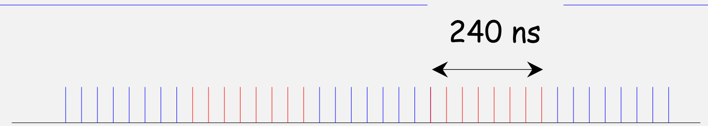
(not to scale)



CLIC Layout at 3 TeV

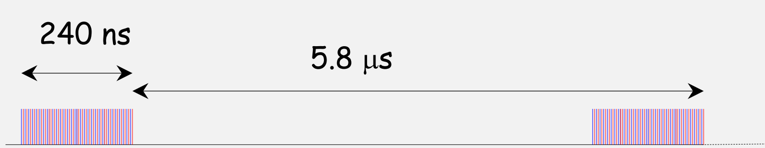


Drive beam time structure - initial



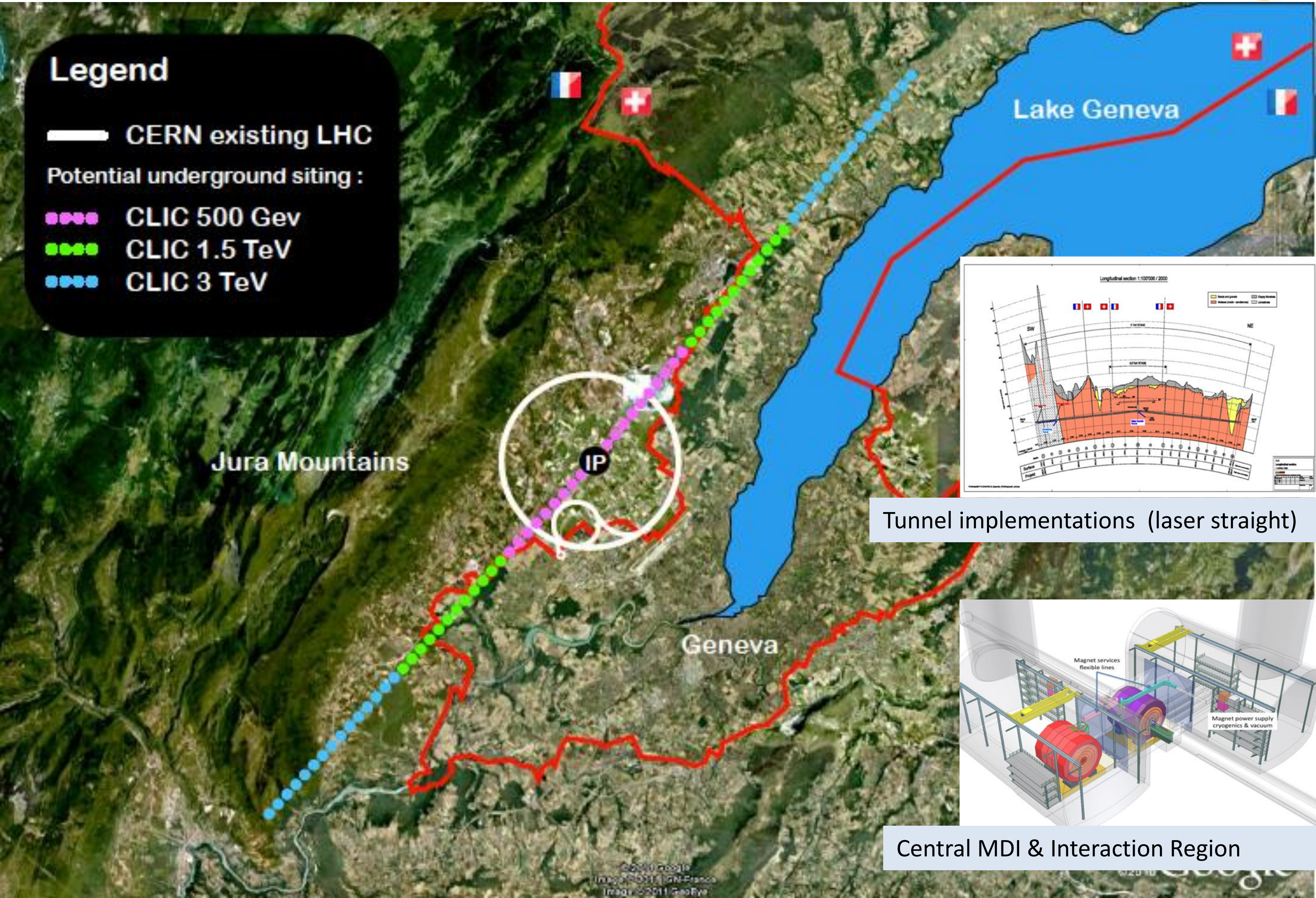
140 μs train length - 24 × 24 sub-pulses
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final



24 pulses – 101 A – 2.5 cm between bunches

CLIC near CERN



Tunnel implementations (laser straight)

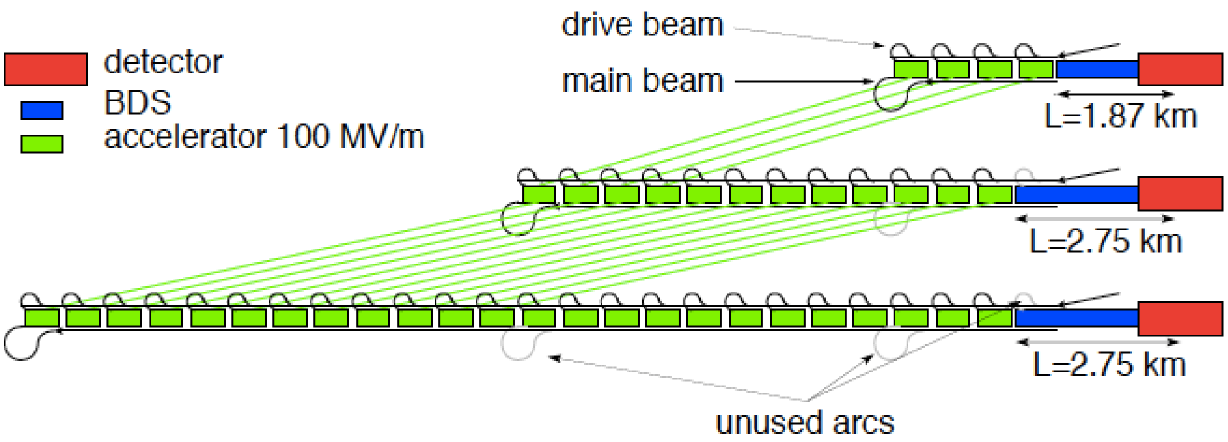
Central MDI & Interaction Region

CLIC Collaboration

Accelerator collaboration has ≈ 50 institutes and the detector collaboration ≈ 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

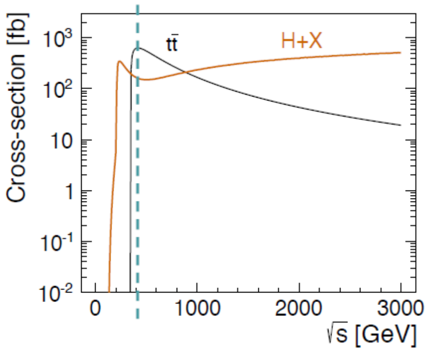
- Second stage: E_{cms}=O(1.5TeV)

- Final stage: E_{cms}=3TeV, $L_{0.01}$=2x10^{34}cm^{-2}s^{-1}, $L_{0.01}$/L>0.3

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,

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

⇨ **$\sqrt{s}$ ~ 380 GeV**

Still good for HZ
Provides valid top quark program

Top pair production

⇨ $\sqrt{s}$ > 360 GeV

Top pair BSM

⇨ $\sqrt{s}$ > 360 - ? GeV

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Automatic Parameter Determination

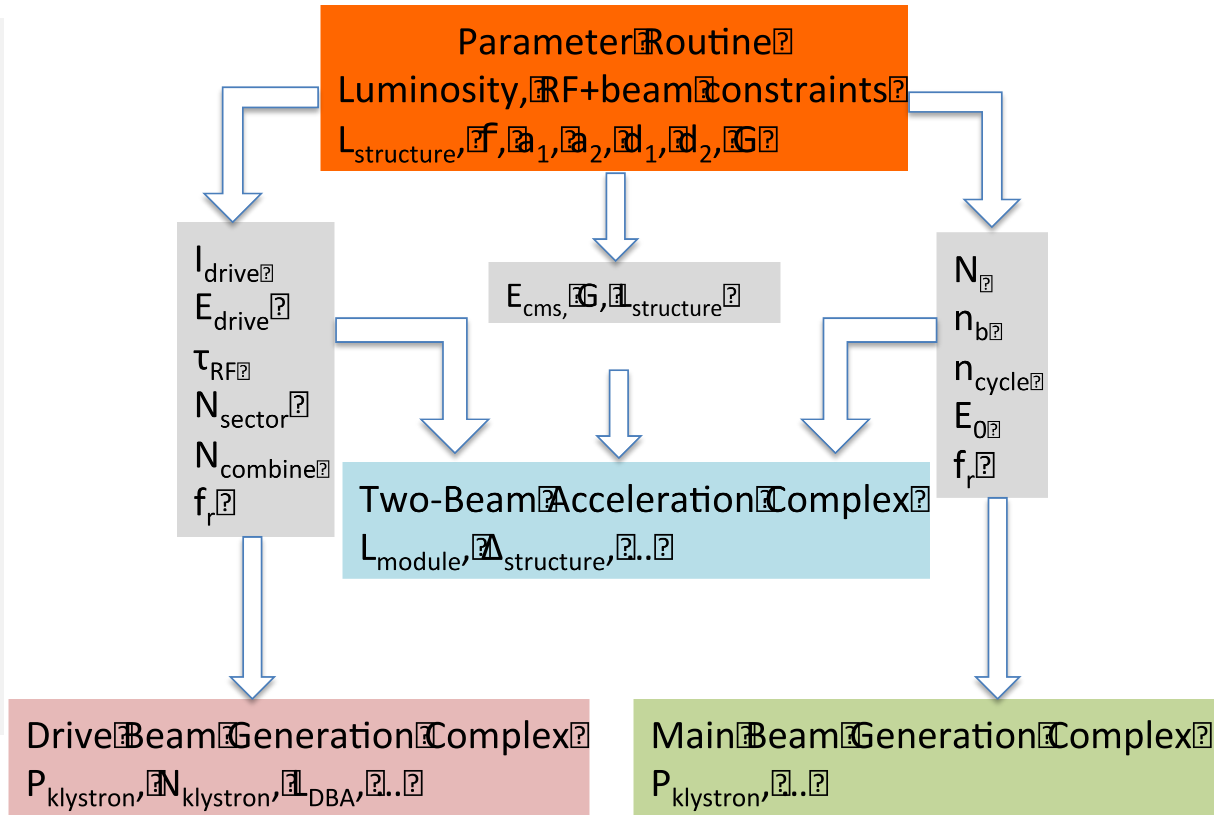
Structure design fixed by few parameters

$a_1, a_2, d_1, d_2, N_c, \phi, G$

Beam parameters derived automatically to reach specific energy and luminosity

Consistency of structure with RF constraints is checked

Repeat for 1.7 billion cases

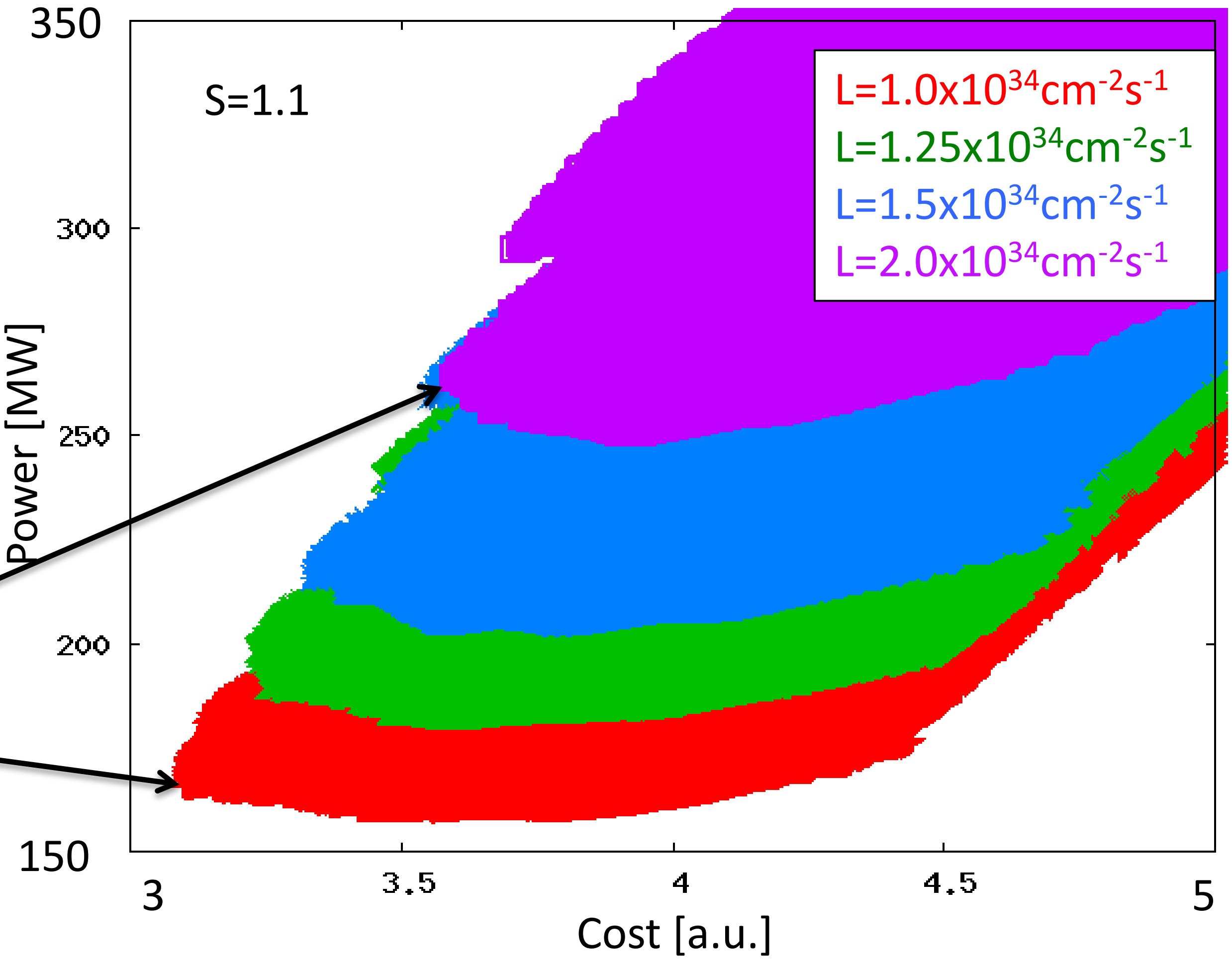


Design choices and specific studies

- Use 50Hz operation for beam stability
- Scale horizontal emittance with charge to keep the same risk in damping ring
- Scale for constant local stability in main linac, i.e. tolerances vary but stay above CDR values
- BDS design similar to CDR, use improved β_x-reach as reserve
- …

Optimization at 360GeV

(Each point represents an accelerating structure design. High-gradient performance is based on testing program results and high-gradient scaling laws – WW)

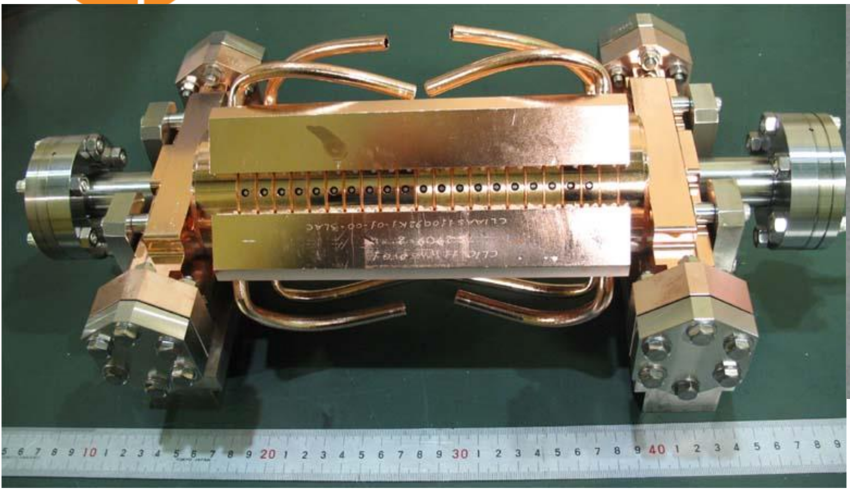


Luminosity goal significantly impact minimum cost
For $L=1x10^{34}cm^{-2}s^{-1}$ to $L=2x10^{34}cm^{-2}s^{-1}$:

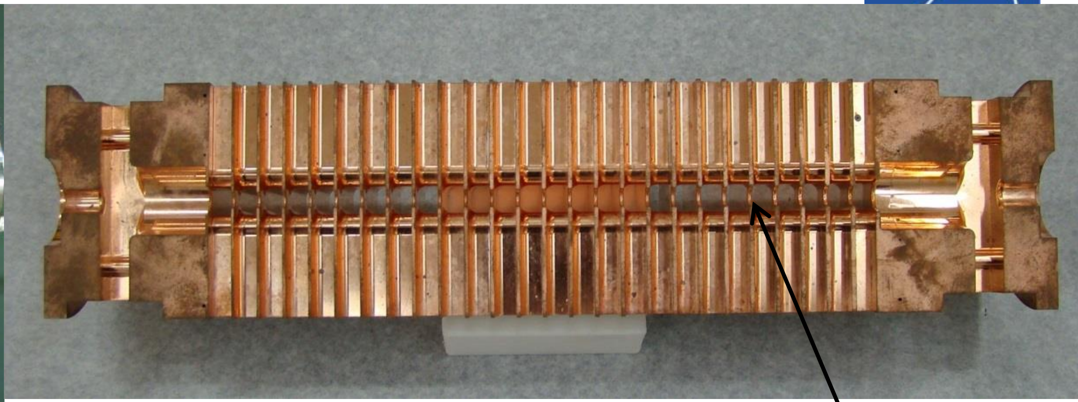
Costs 0.5 a.u.
And O(100MW)

Cheapest machine is close to lowest power consumption => small potential for trade-off

CLIC accelerating structure



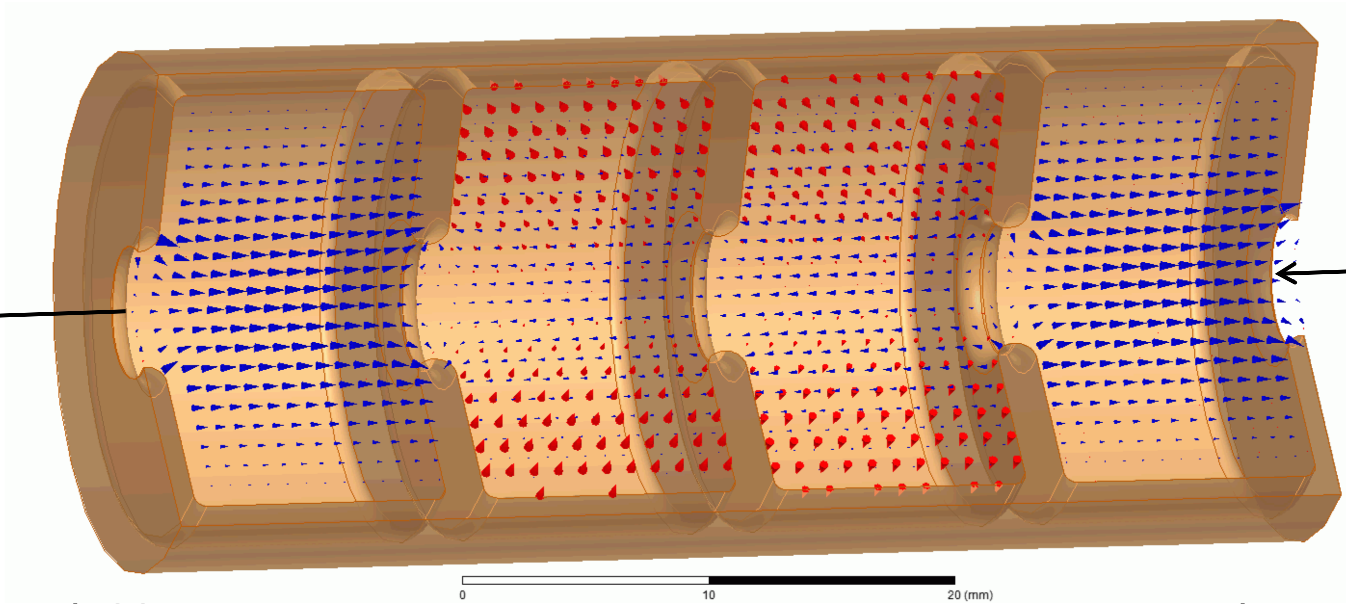
Outside



Inside

11.994 GHz X-band

6 mm diameter
beam aperture



beam
propagation
direction

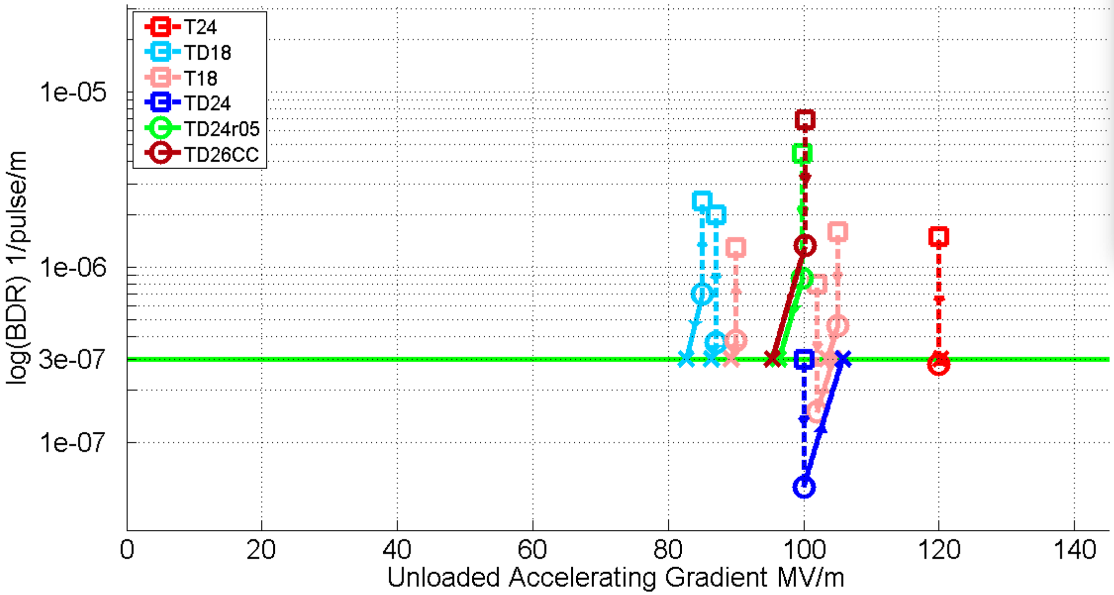
Concept

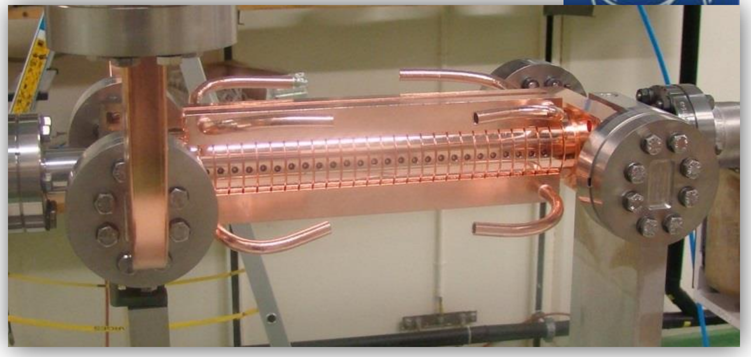
High gradient – compact and potentially cheaper

State-of-the acceleration:
Normal conducting:
28 MV/m SwissFEL
35 MV/m SACLA
Superconducting:
24 MV/m European XFEL
31.5 MV/m ILC

Our goals:
100 MV/m CLIC
60-80 MV/m compact XFELs
50 MV/m low-β proton therapy linacs

X-band accelerating structure development





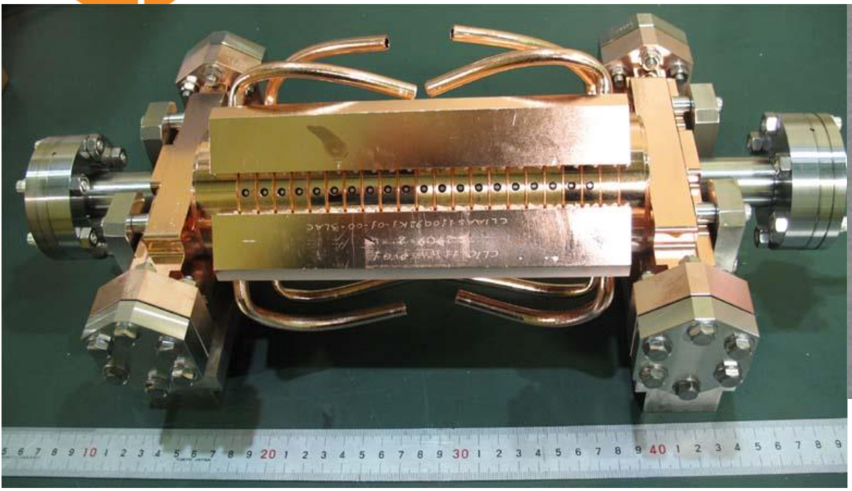
Operating frequency	12 GHz
Accelerating gradient	100 MV/m
Peak surface electric field	250 MV/m
Pulse length	200 ns
Repetition rate	50 Hz
Input power	50 MW
Breakdown rate	$<10^{-7}$ BD/pulse/m

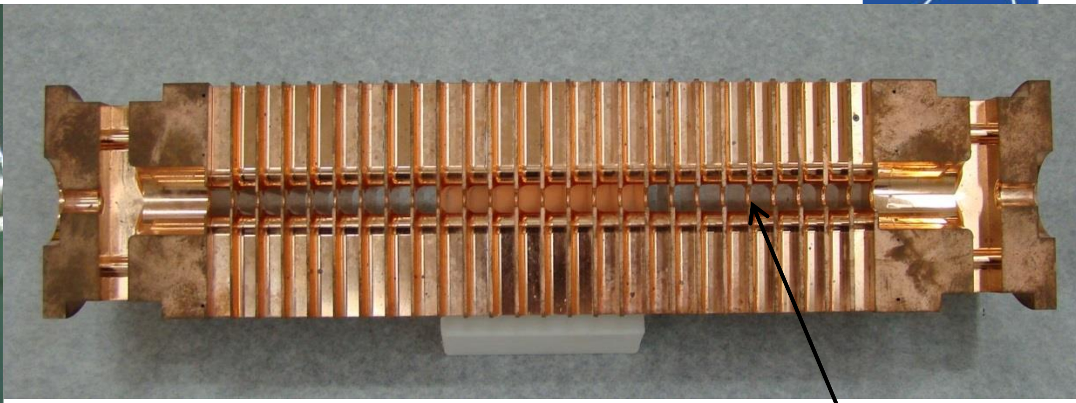
100 MV/m has been clearly demonstrated in prototype structures, but only in a limited number.

In order to improve statistics, make lifetime tests and investigate variants we have invested significant resources into increasing testing capacity with:

Three klystron-based test stands – **Xbox-1 to 3**.

CLIC accelerating structure



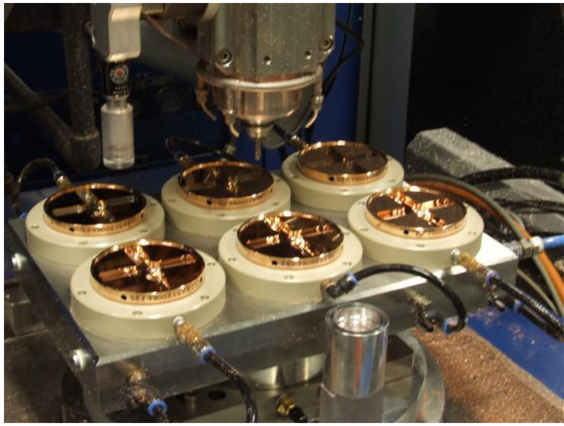


Inside (cut)

6 mm diameter
beam aperture,
25 cm long

Outside

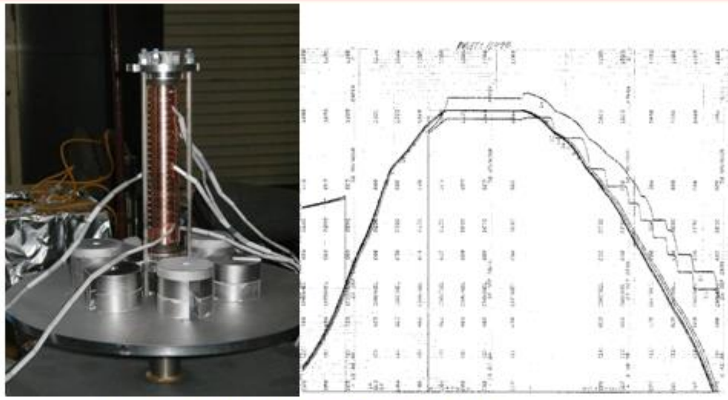
Micron-precision turning and milling.



Heat treatment and material structure

Stacking disks

Diffusion Bonding of T18_vg2.4_DISC



Pressure: 60 PSI (60 LB for this structure disks)

Holding for 1 hour at 1020° C

Vacuum Baking of T18_vg2.4_DISC

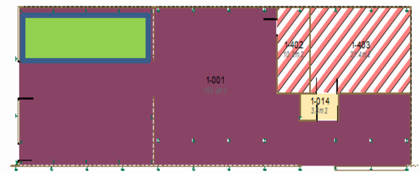
650° C

10 days

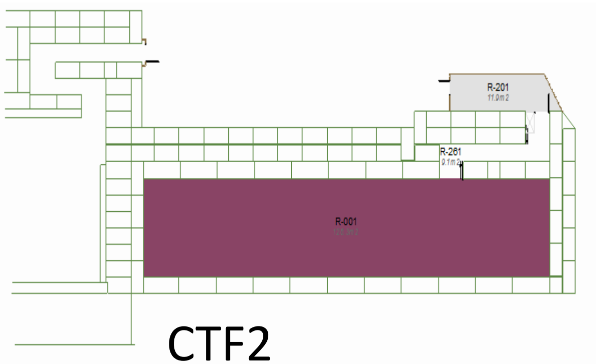
Temperature treatment for high-gradient developed by NLC/JLC

Find the bonding plane!

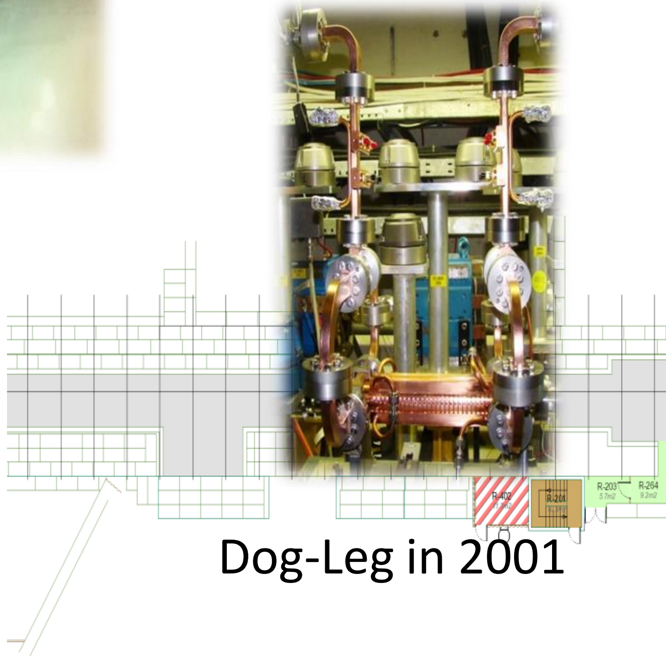
Xbox1 in b. 2013



CTF3 klystron gallery



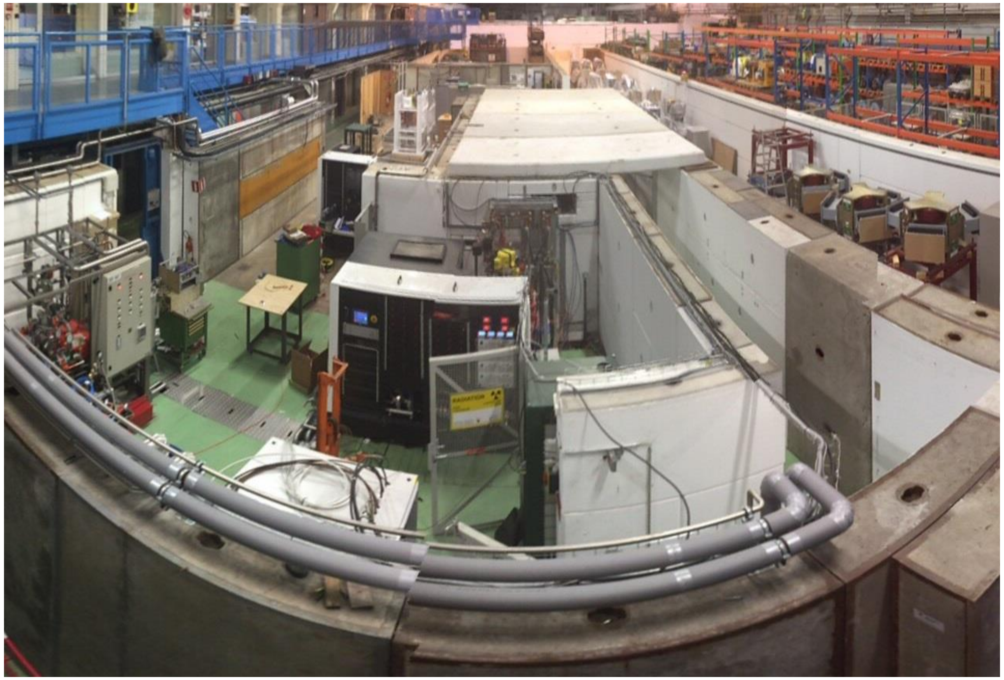
CTF2

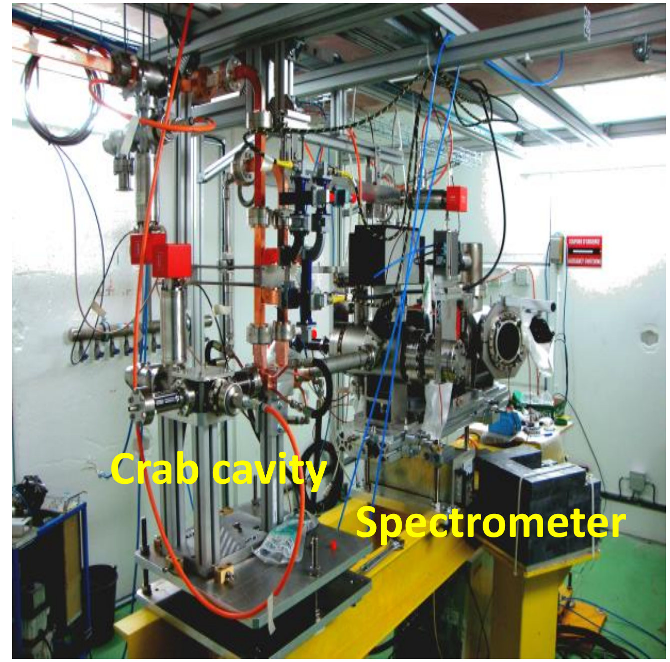


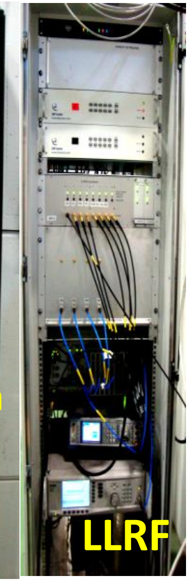
Dog-Leg in 2001

N. Catalan Lasheras

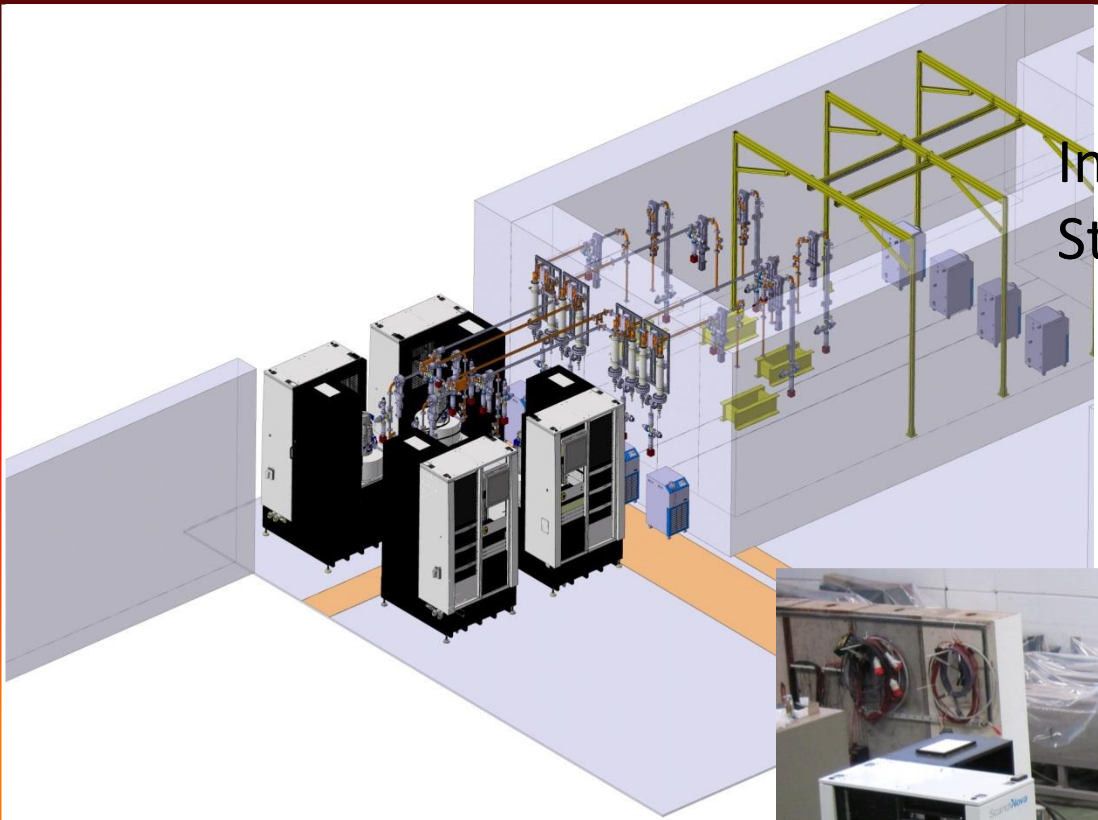
Xbox2 in b. 150



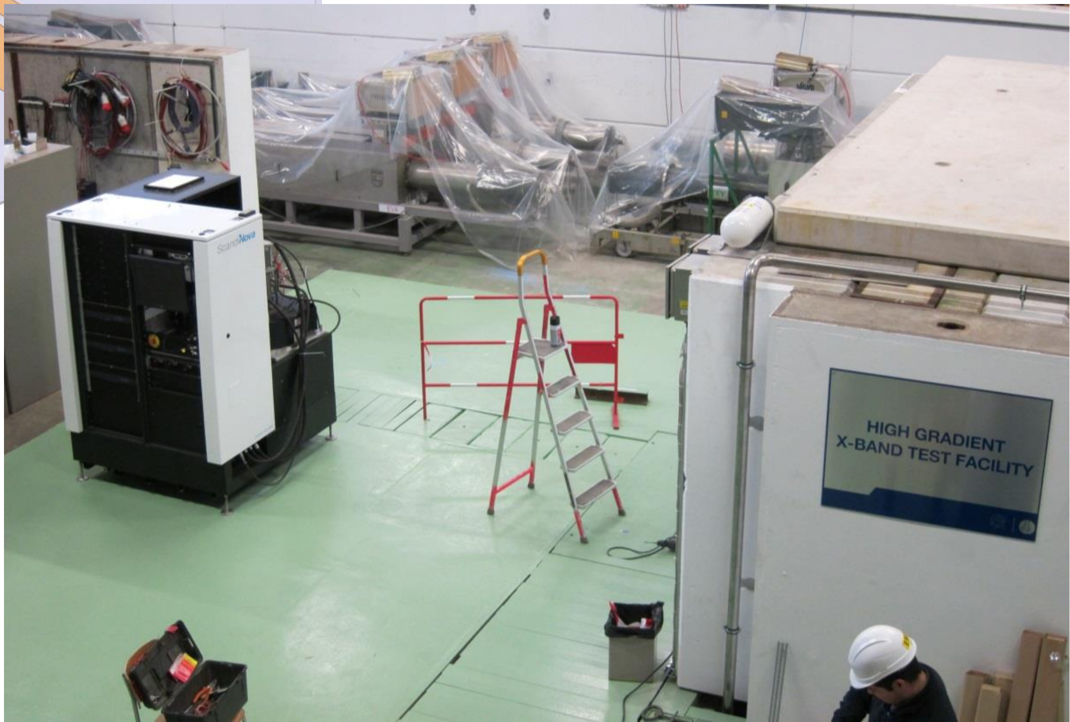




Xbox3 in b. 150

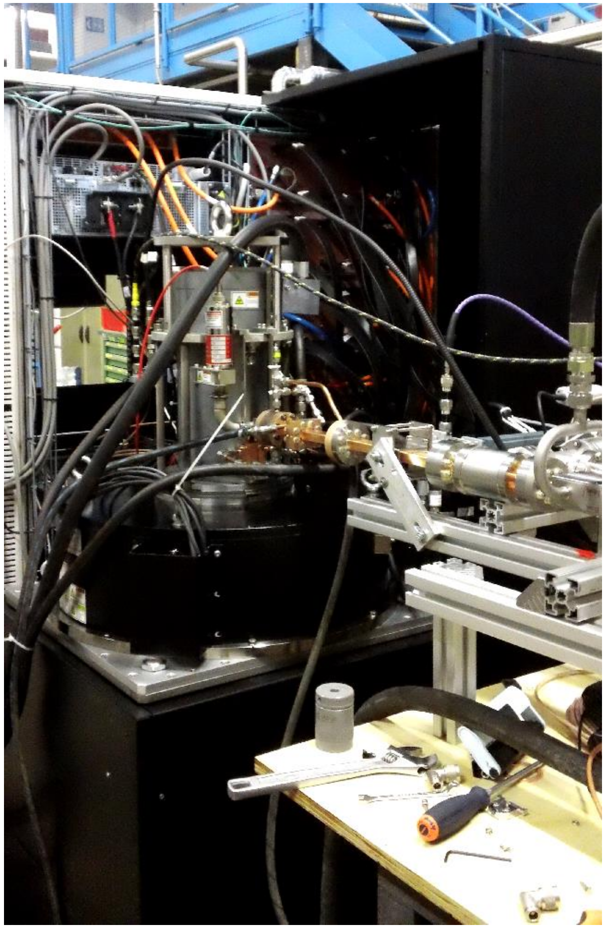


Installation progressing well.
Start-up May/June



X-band klystrons

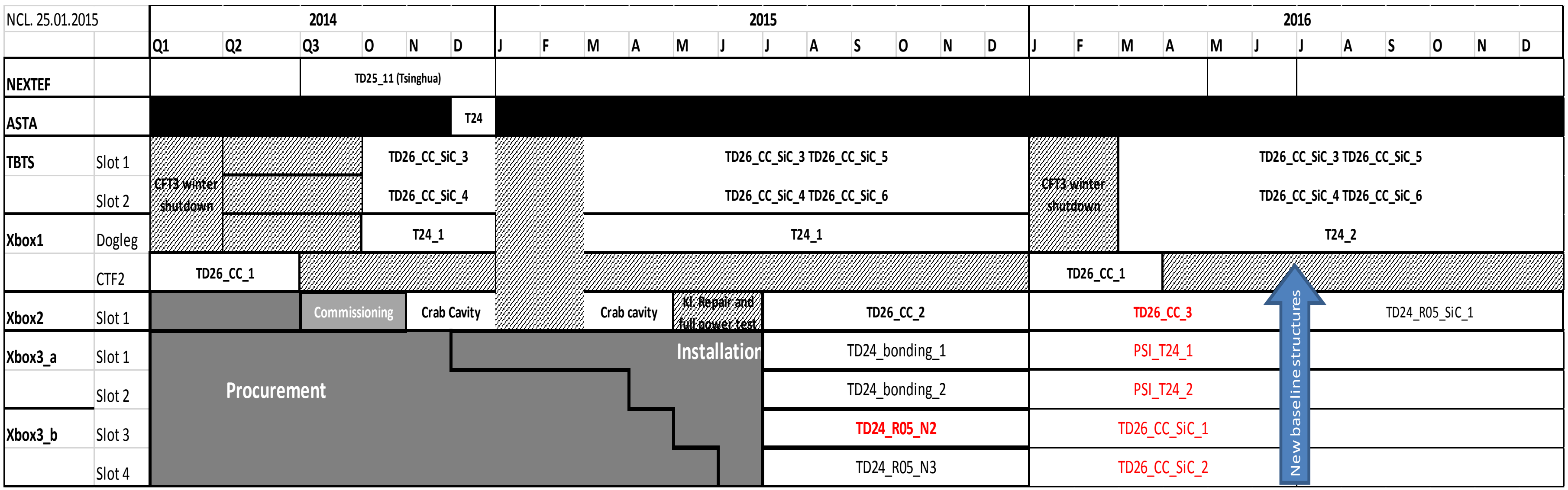
We now have two types of *commercial* X-band power sources running at CERN.



Toshiba 6 MW, 5 μs, 400 Hz

CPI 50 MW, 1.5 μs, 50 Hz

Our rf structure testing schedule

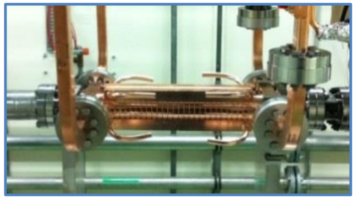


Large increase in the testing capability

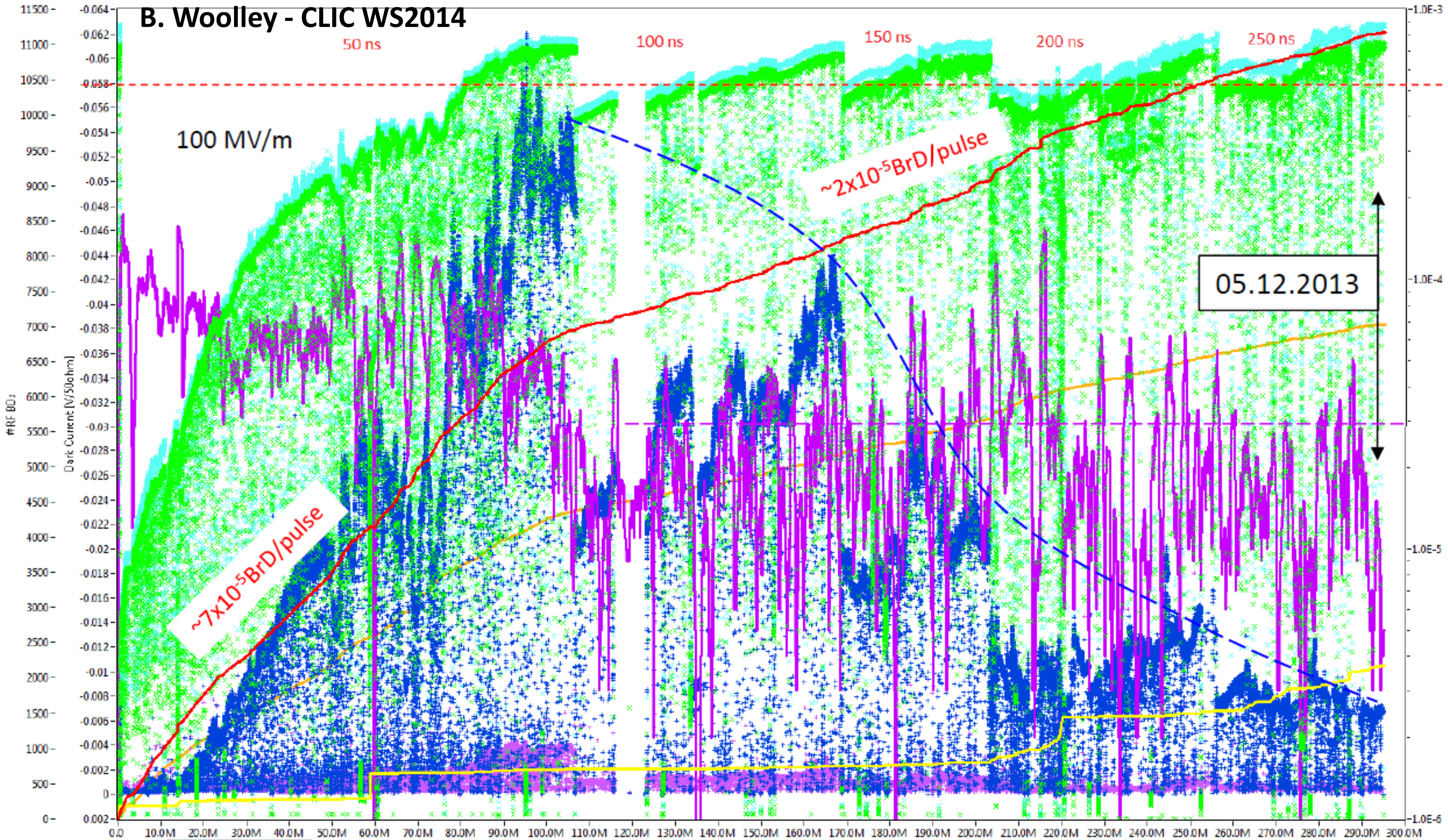
Xbox-1: TD26CC#1 conditioning history

Automatic operation by a conditioning algorithm

[see J.Tagg presentation]

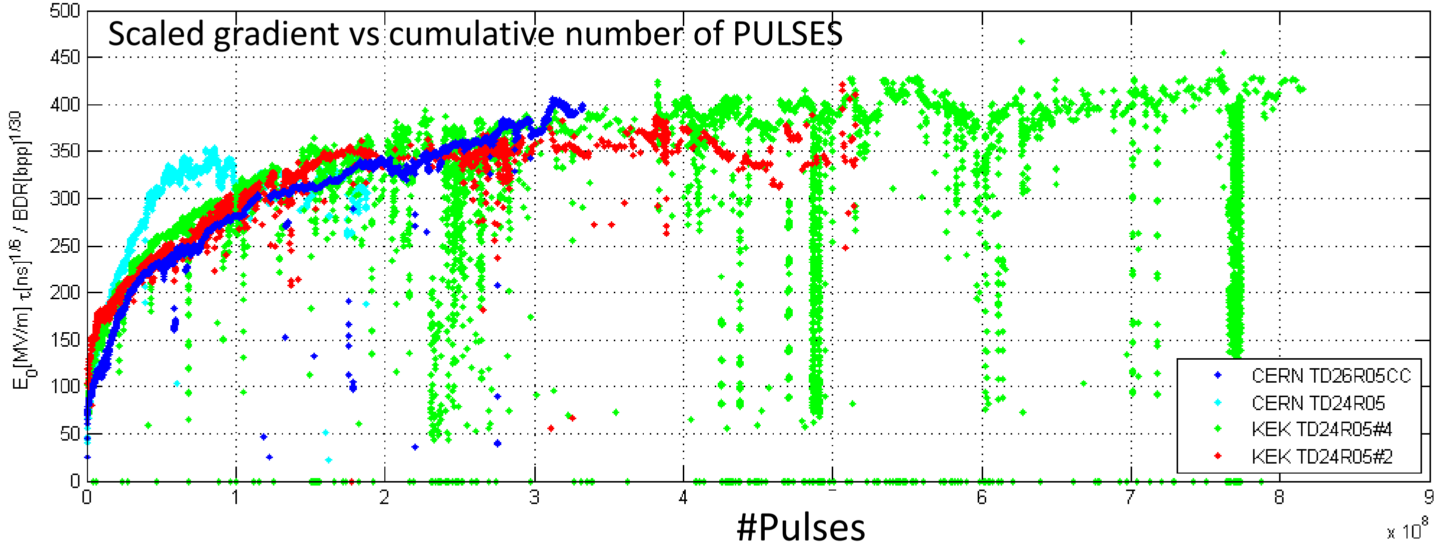


11168 BDs



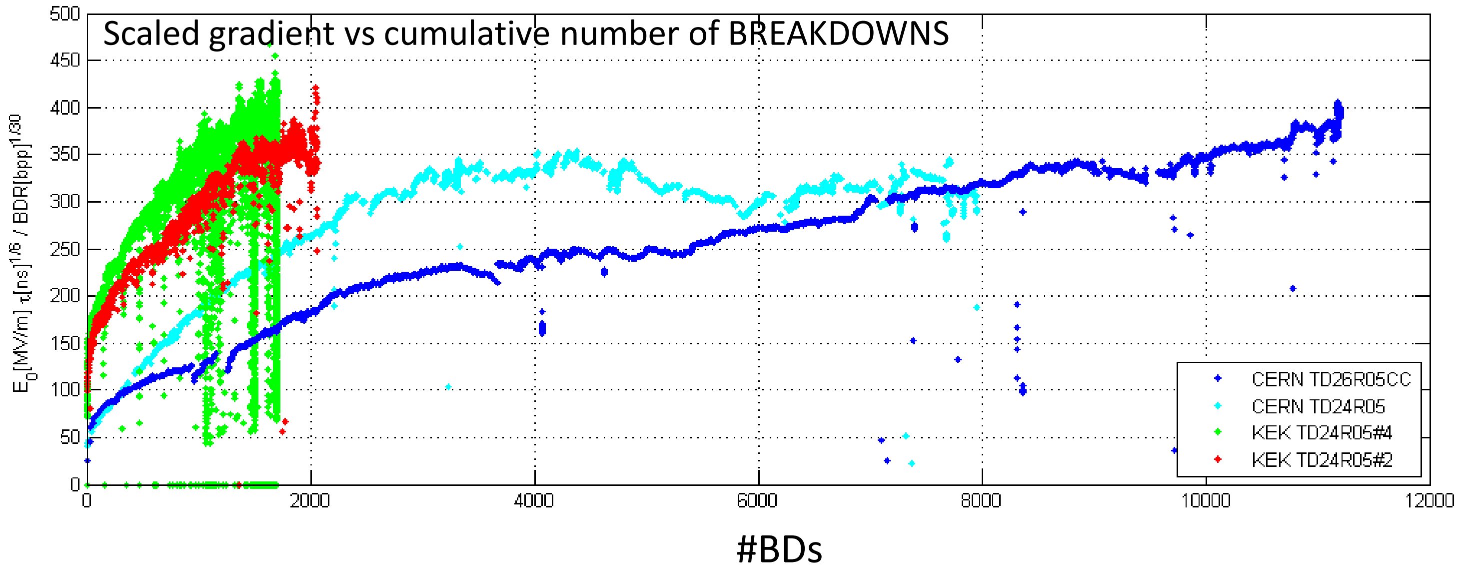
Comparison of conditioning evolution

E_0^*

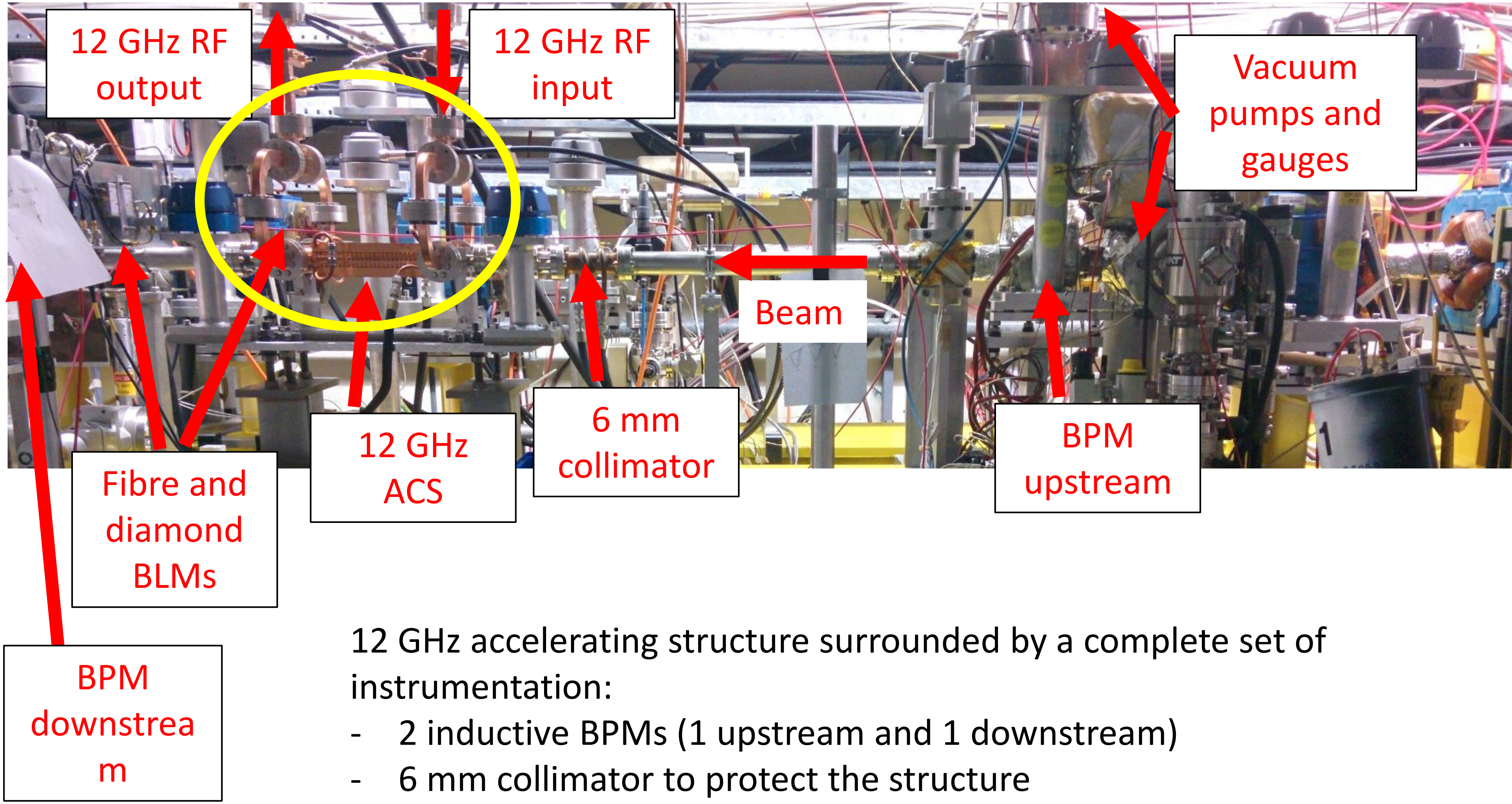


Conditioning to high-gradient is given by the pulses not the breakdowns!

E_0^*



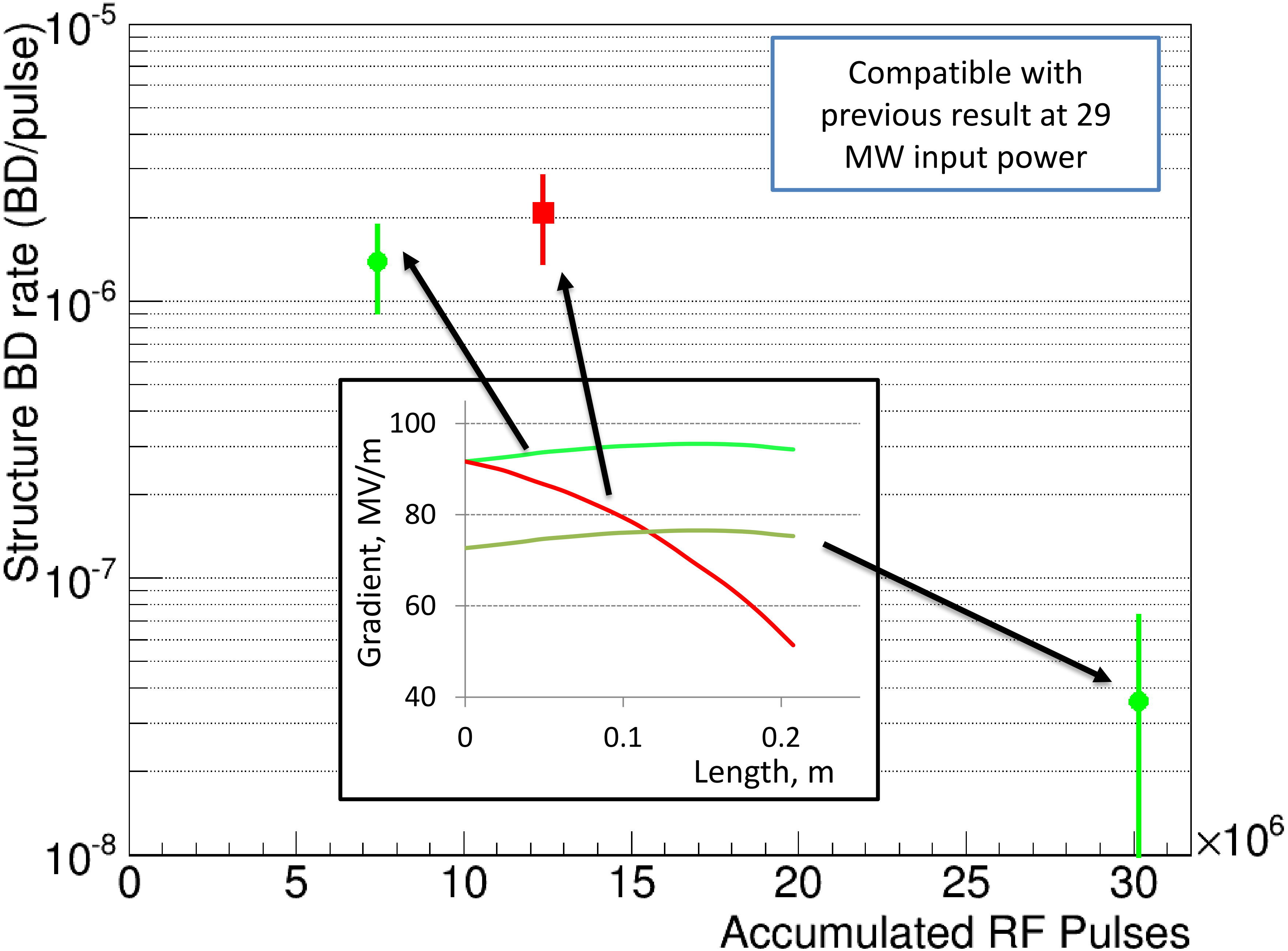
Diagnostic, control and protection



12 GHz accelerating structure surrounded by a complete set of instrumentation:

- 2 inductive BPMs (1 upstream and 1 downstream)
- 6 mm collimator to protect the structure
- Fibre optic and diamond beam loss monitors
- Vacuum pumps and gauges in beam chamber and RF waveguides

First Results: BDr

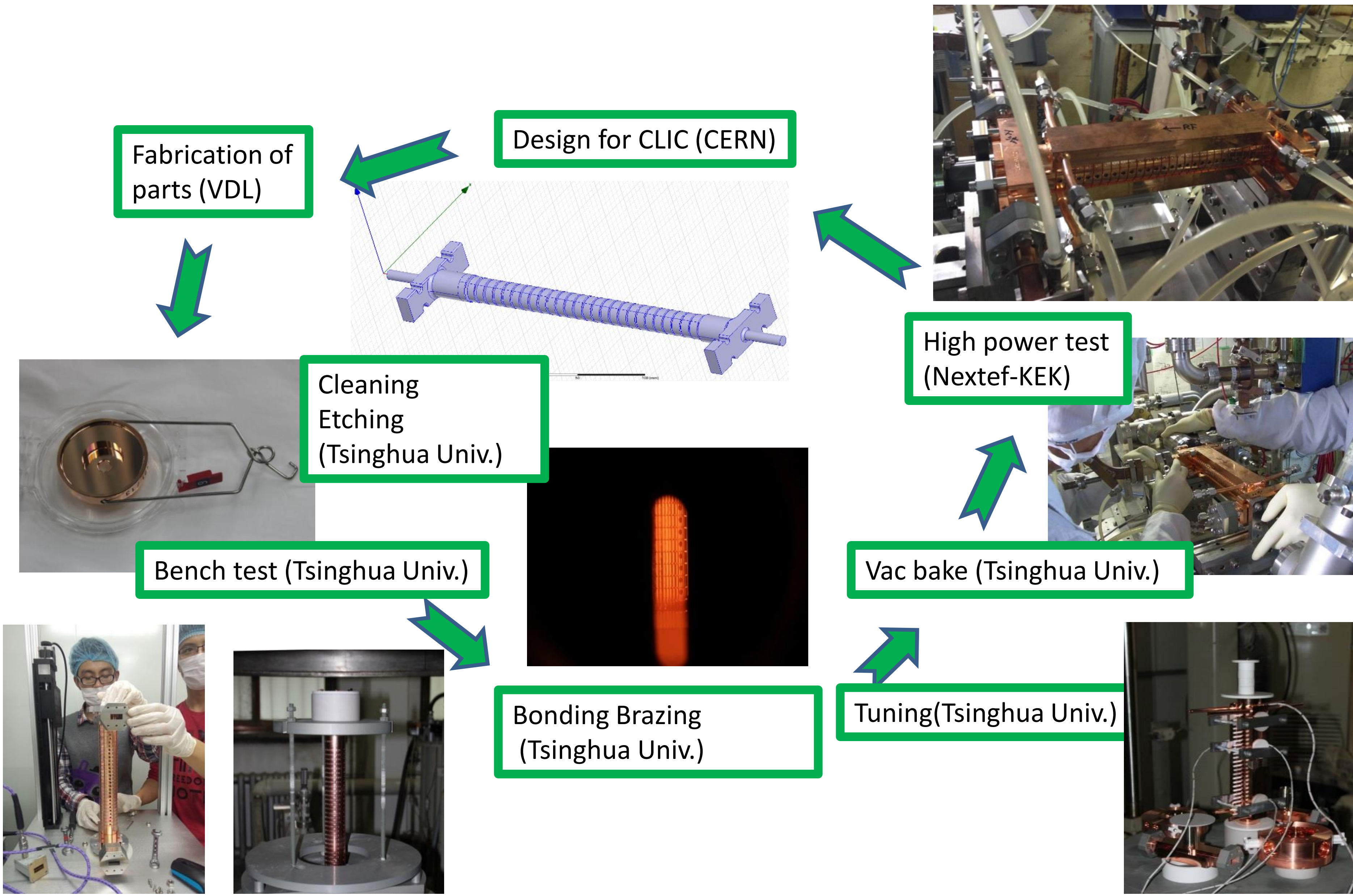


Outreach activities

In order to broaden the technological base for X-band and high gradient we actively pursue fabrication at different laboratories and for different projects.

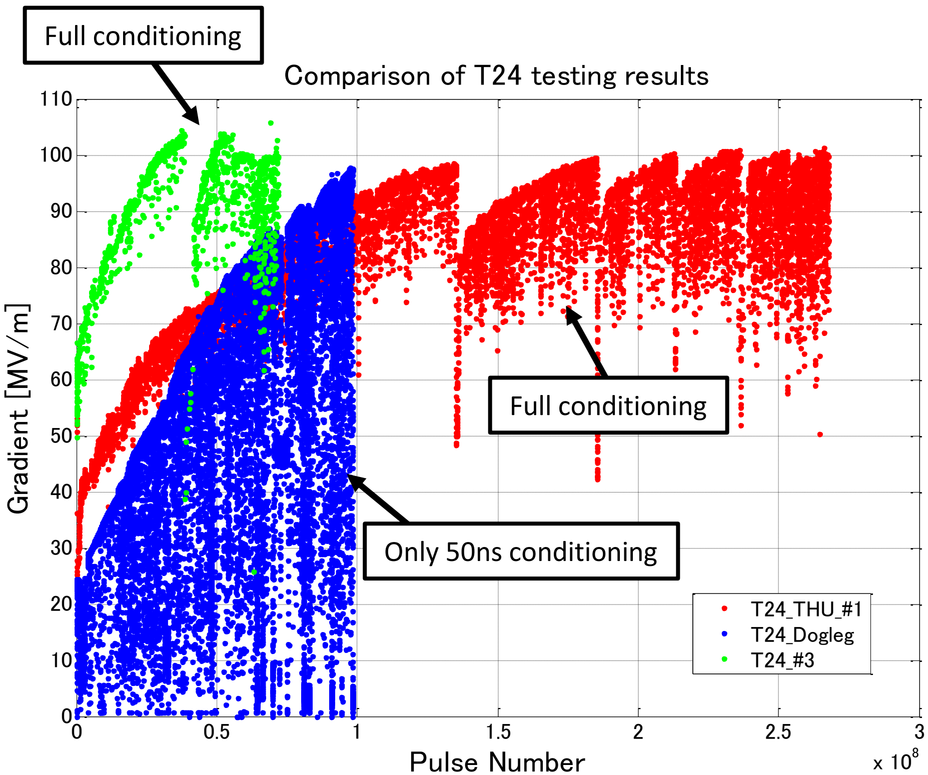
Institute	Structure	Status
KEK	Long history – latest TD26CC	Mechanical design
Tsinghua	T24 - VDL machined, Tsinghua assembled, H bonding, KEK high-power test	At KEK
	CLIC choke	manufacturing tests
SINAP	XFEL structure, KEK high-power test	rf design phase
	T24, CERN high-power test	Agreement signed
	Four XFEL structures	Agreement signed
CIEMAT	TD24CC	Agreement signed
PSI	Two T24 structures made at PSI using SwissFEL production line including vacuum brazing	Mechanical design work underway
VDL	XFEL structure	Interest
SLAC	T24 in milled halves	machining
CERN	3 TeV and 380 GeV	
	KT (Knowledge Transfer) funded medical linac	machining

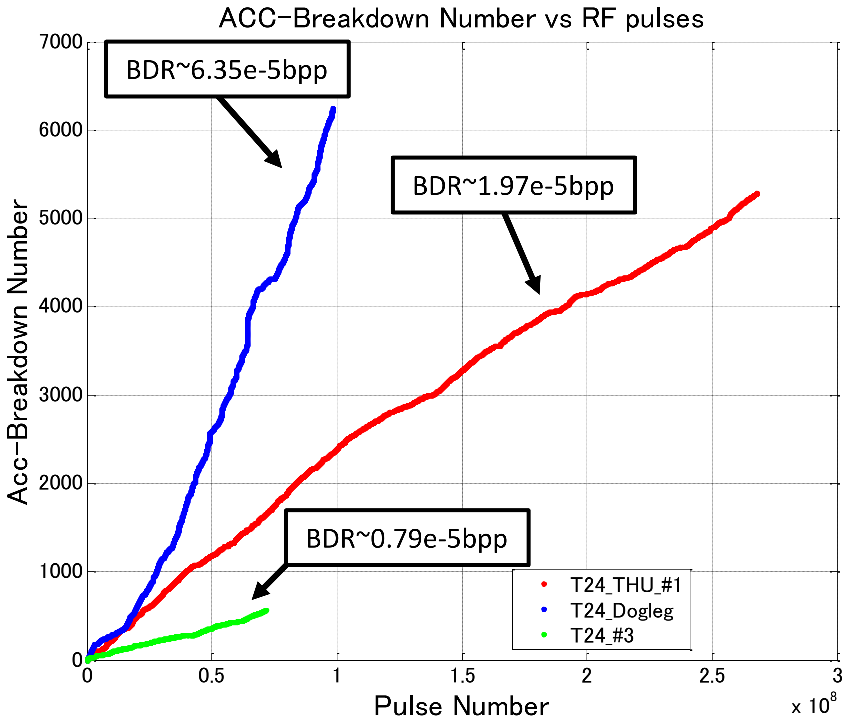
CERN/Tsinghua/KEK collaboration



Compare with other T24 testing results (2)

- T24_THU_#1 costs more time to reach 100 MV/m at 51ns pulse width but having a smaller BDR compared with T24_Dogleg
- T24_#3 shows an excellent performance with higher ramping speed and less breakdowns





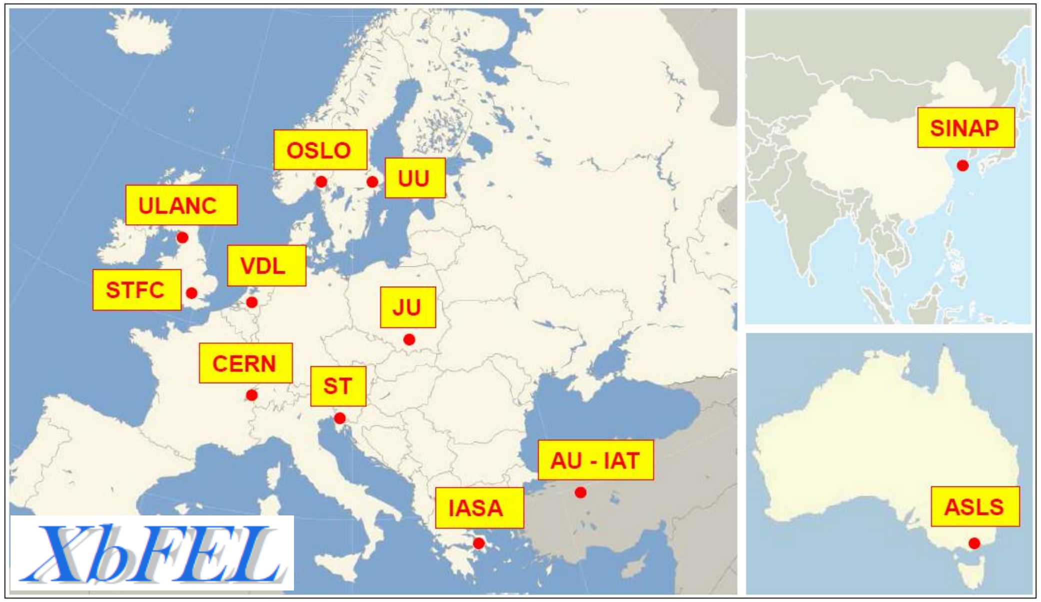
XbFEL

See G. D'Auria Thursday 9:30

A proposal for an EU co-funded Design Study

A core activity of the FEL collaboration

Submitted September 3



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.*

XbFEL

TAC Collaboration

Turkish Accelerator Centre
Infrared FEL TARLA under construction
X-FEL planned

Ankara University (Coordinator)

Gazi University

İstanbul University

Uludağ University

Dumlupınar University

Osmangazi University

Boğaziçi University

Doğuş University

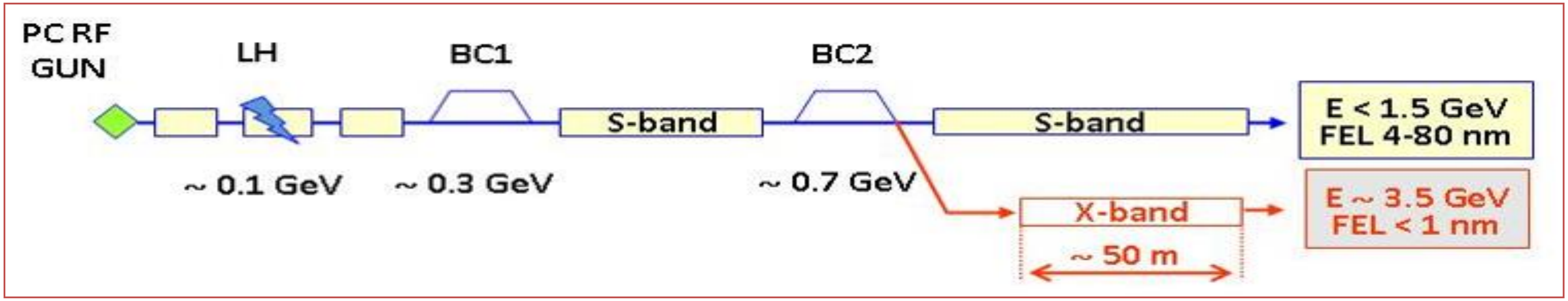
Erciyes University

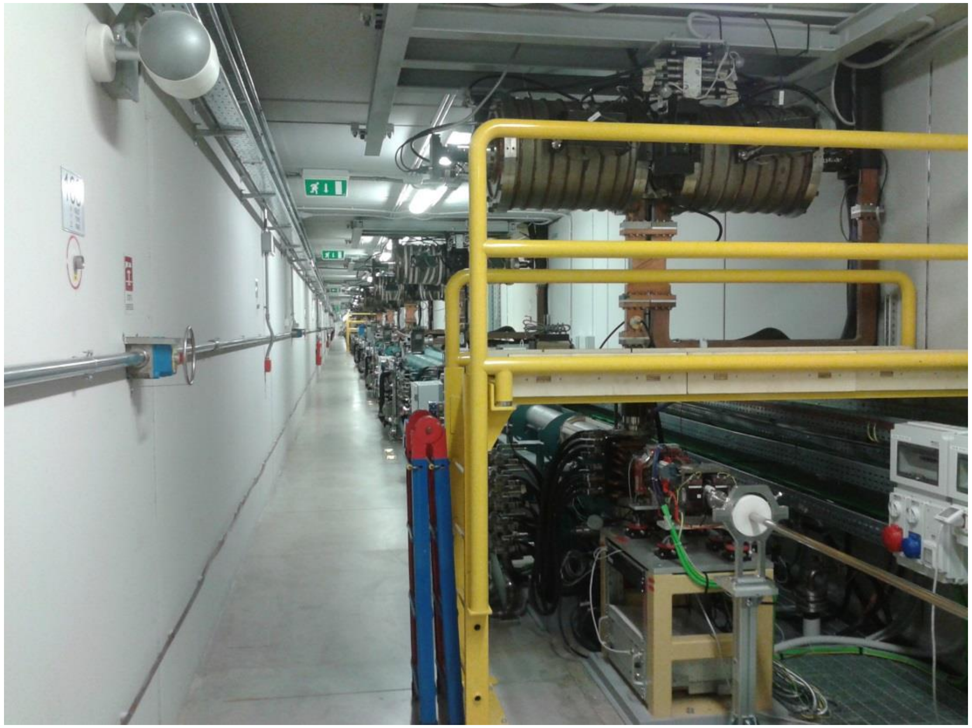
Süleyman Demirel University

Niğde University

Gebze Institude of Technology

ELETTRA





- Existing FEL is based on injector for synchrotron (FERMI)
- Upgrade with X-band to increase beam energy for FEL

Table 3. FEL3 expected performance.

Undulator period	30	mm
Undulator parameter	1	
Fundamental wavelength	0.5	nm
Pierce parameter	0.11%	
3-D Gain length	1.6	m
3-D Saturation length	26	m
Peak power at saturation	5.6	GW

Shanghai Photon Science Center at SINAP

AXXS

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

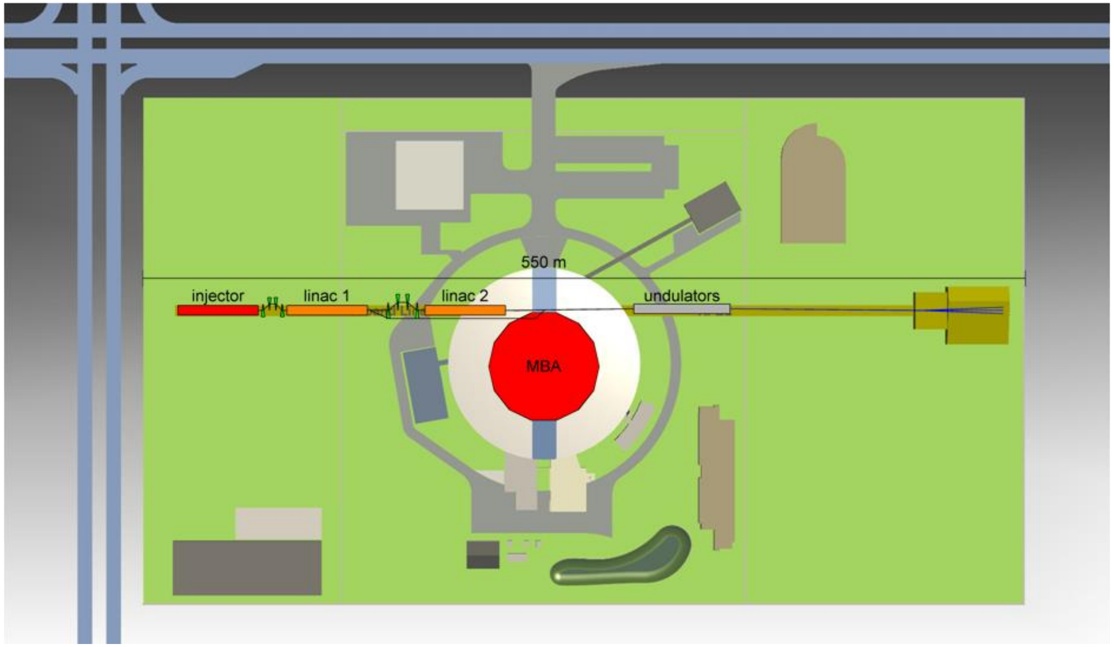
CENTRE FOR ADVANCED MOLECULAR IMAGING
AN ARC CENTRE OF EXCELLENCE

AXXS – Australian X-band X-ray Source
AXXS n. /ˈæksɪs/ *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

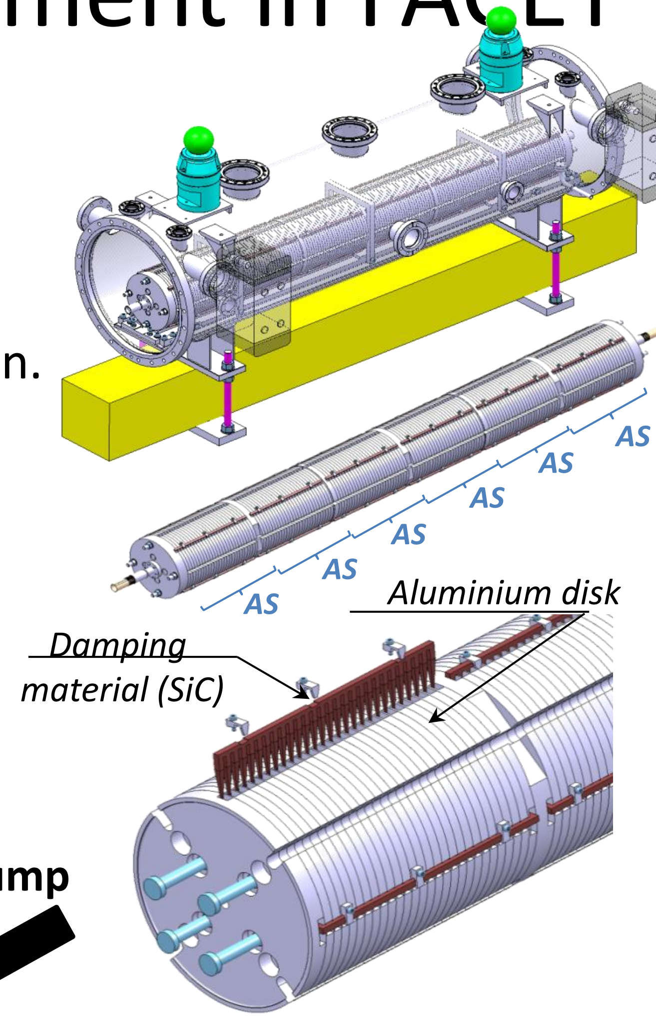
- Site constraint 550 m:

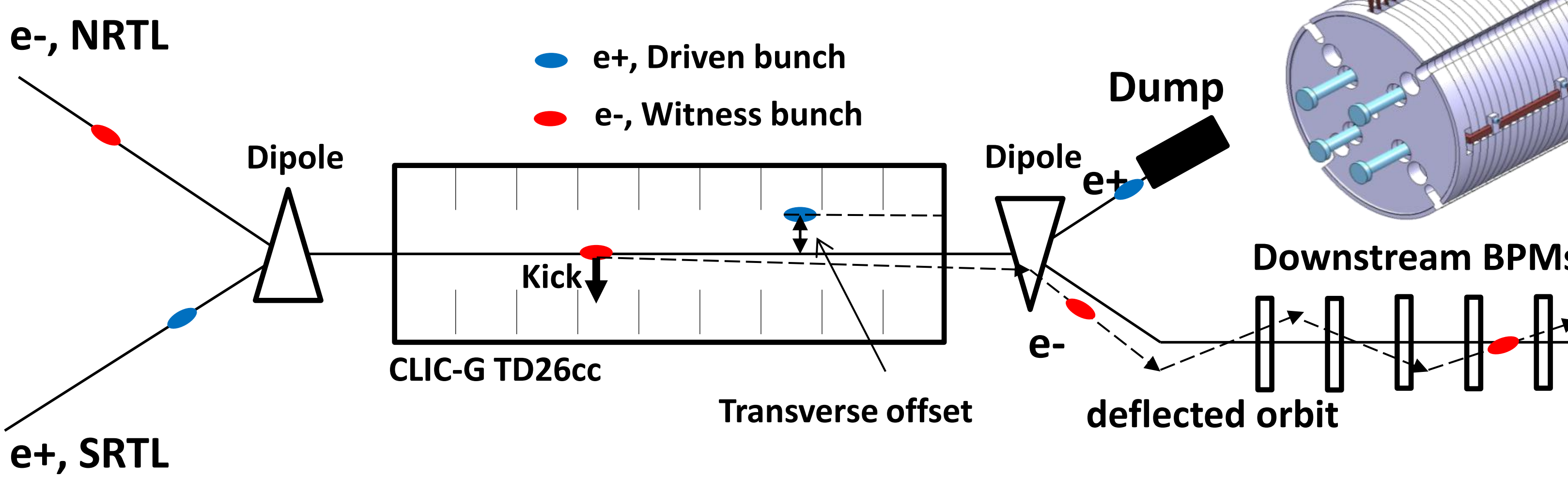
- Same tunnel, energy and source points for storage ring upgrade.
- Time constraints: need to finish building out the remaining beamlines before justifying a new ring or FEL.



Direct wakefield measurement in FACET

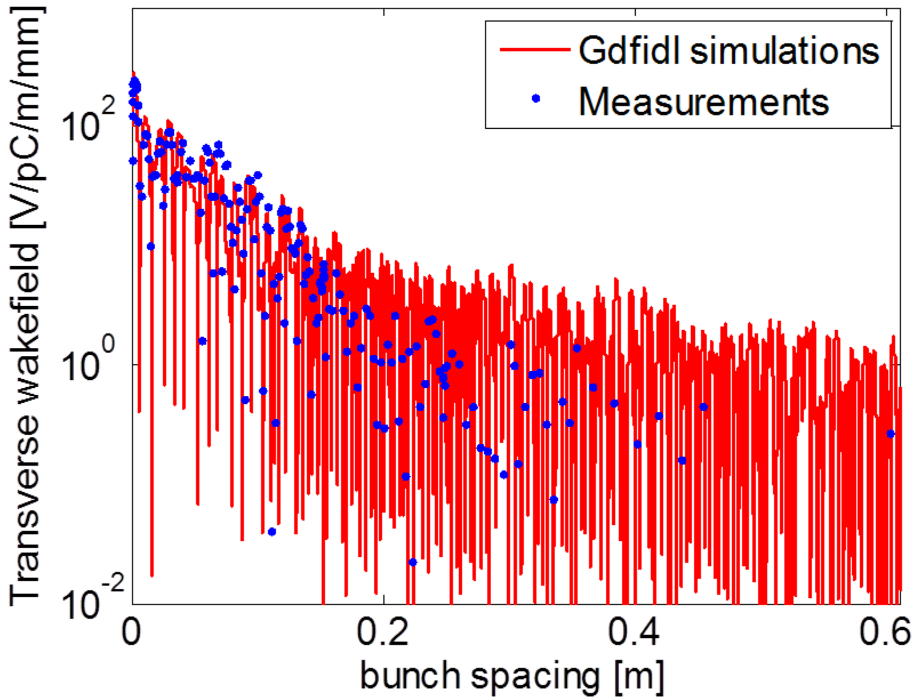
- Prototype structure are made of aluminium disks and SiC loads (clamped together by bolts).
- 6 full structures, active length = 1.38m
- FACET provides 3nC, 1.19GeV electron and positron.
- RMS bunch length is near 0.7mm.
- Maximum orbit deflection of e- due to peak transverse wake kick (1mm e+ offset): 5mm, BPM resolution: 50um

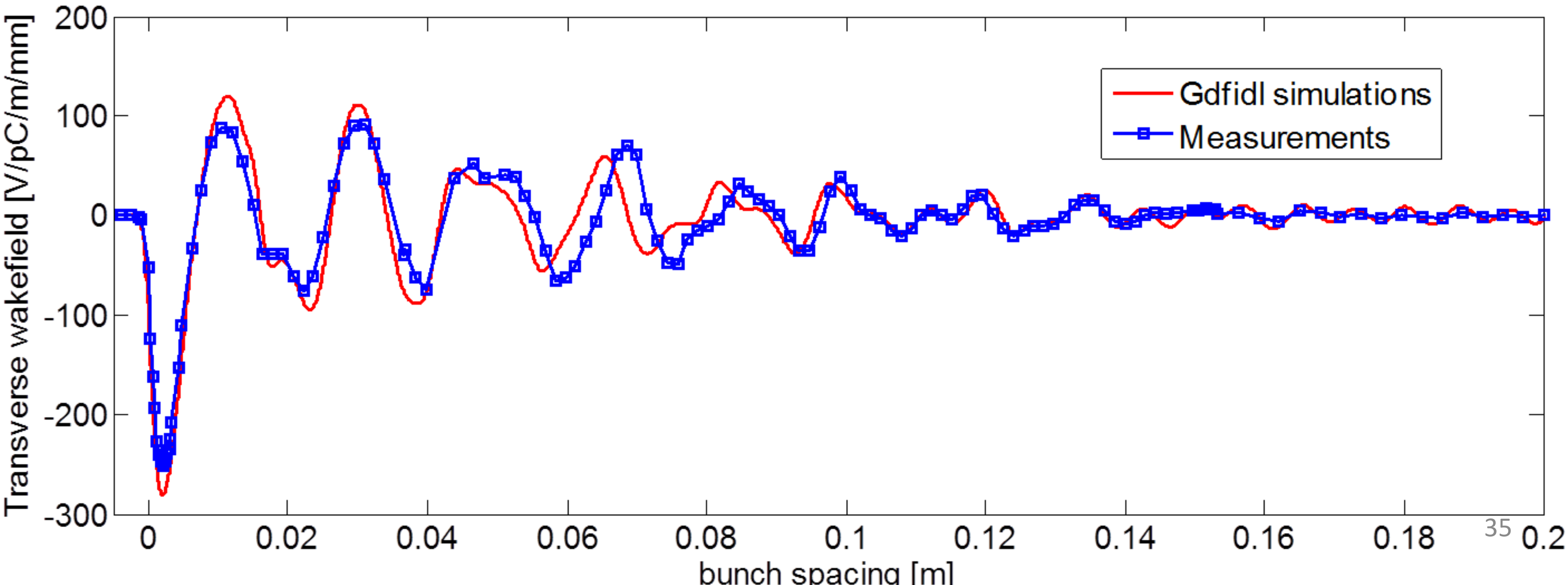




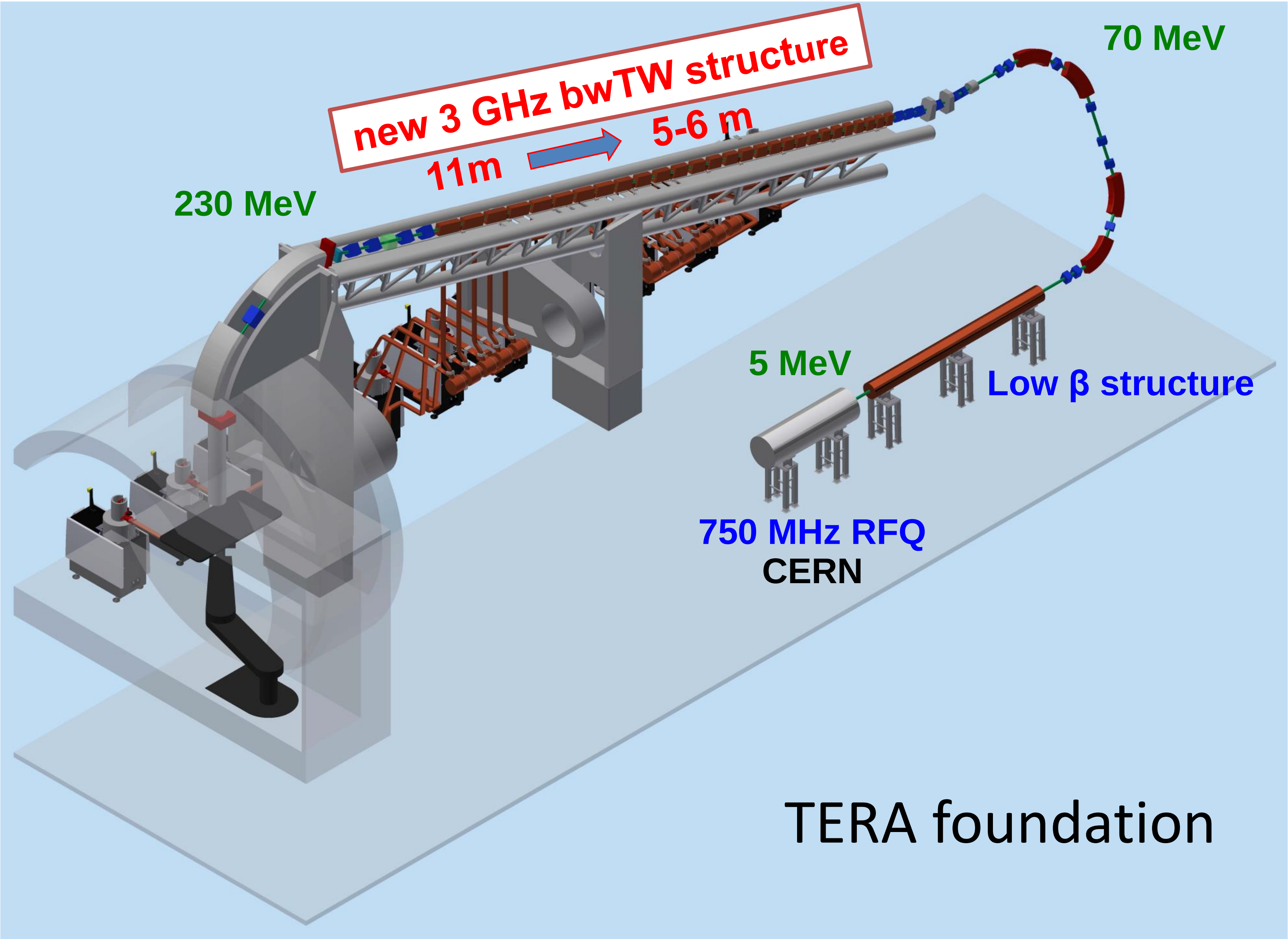
Final results

- We measure the absolutely wakefield value, peak value 10% lower than simulations.
- Wake potential at second bunch seperation = 4.5V/pC/m/mm.
- Decay faster than simulation.

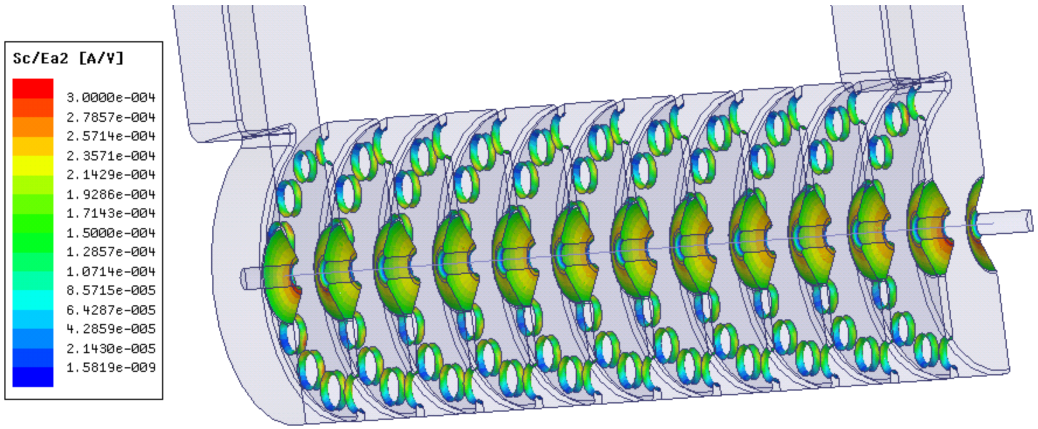


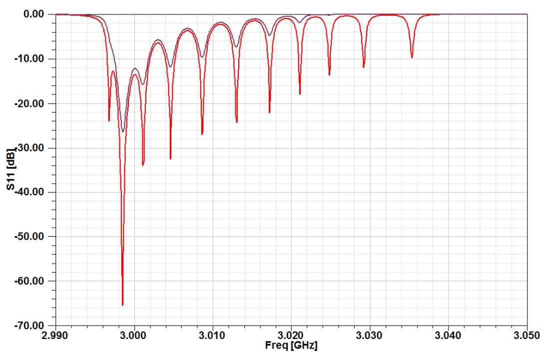


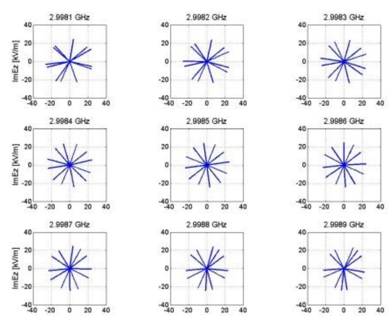
The TULIP Project

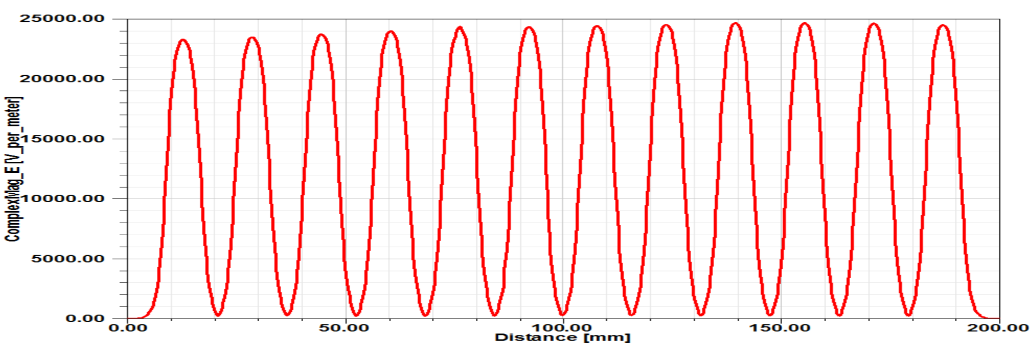


RF design



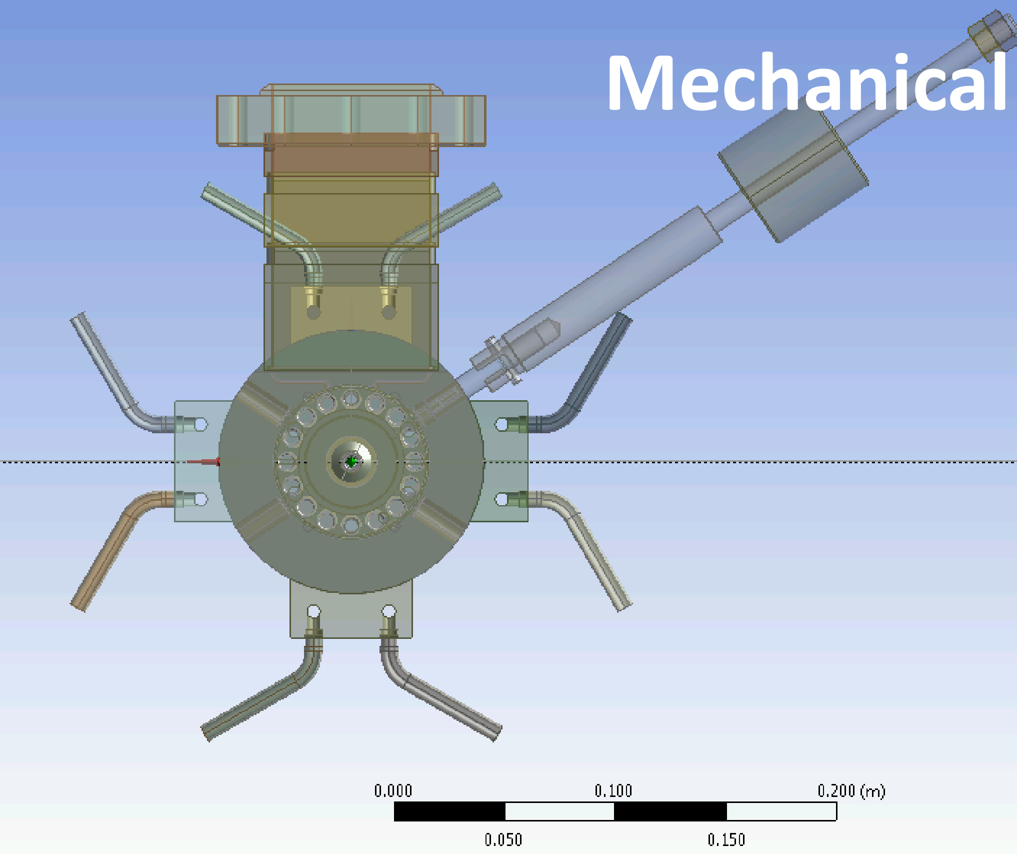


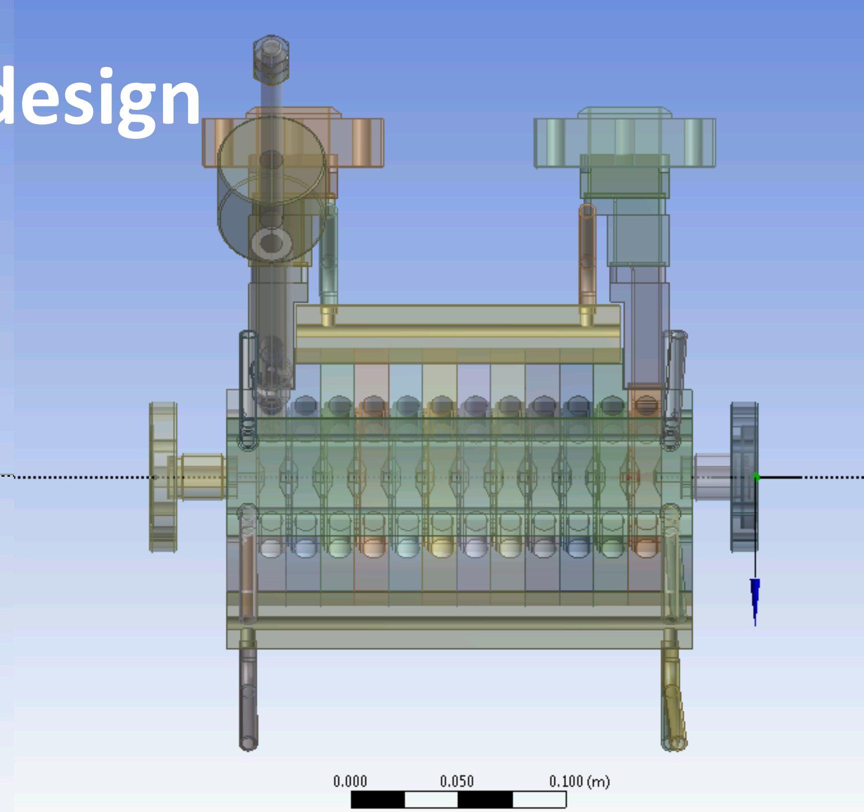




- The Sc/Ea^2 constraint has been widely respected
- A reflection lower than -50 dB at the resonant frequency of 2.9985 GHz has been reached
- Even electric field profile along the structure
- Phase advance of 5π/6 at the operating frequency chosen

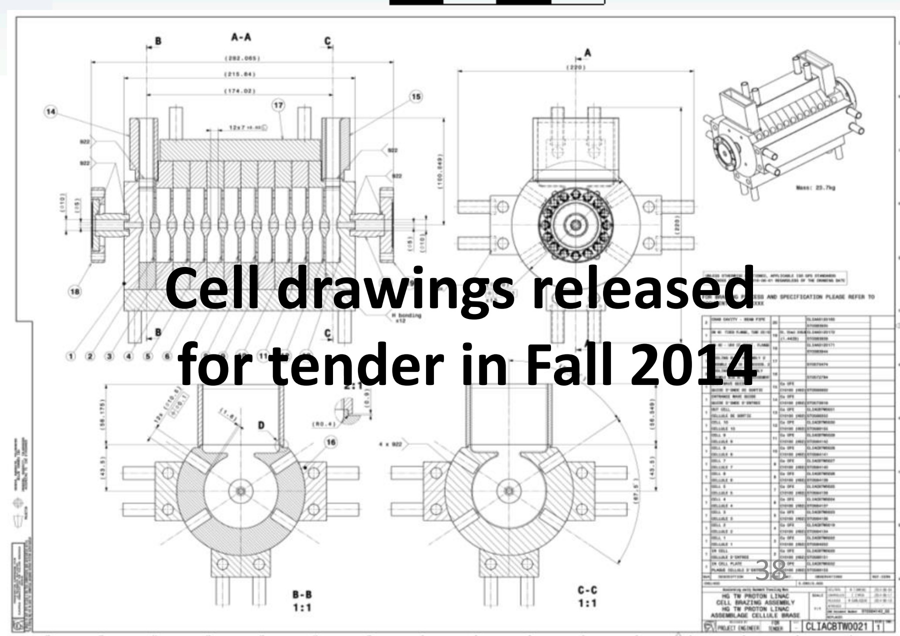
Mechanical design





<u>**How did we come to this?**</u>

- Tolerances specification
- Creep analysis and test
- Tuning analysis and test
- Thermal and stress analysis



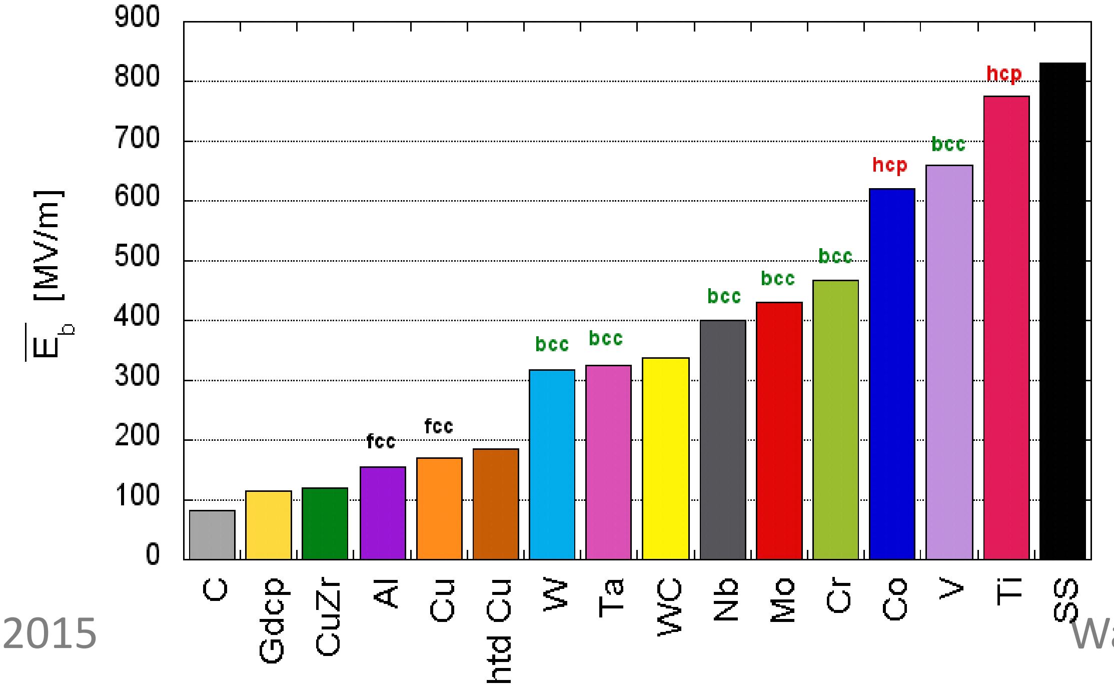
Cell drawings released for tender in Fall 2014

High-surface field R&D

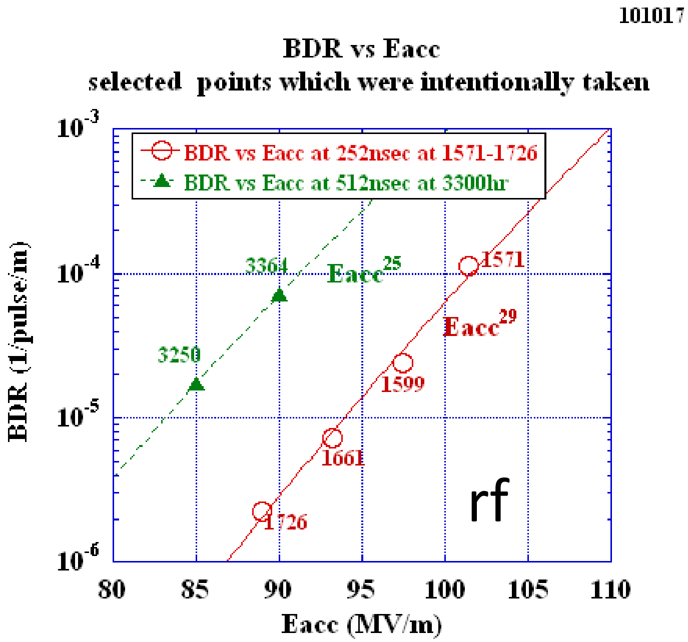
In order to support the high-gradient rf development, we also have a small collaboration studying the fundamental physics and material science of high surface fields.

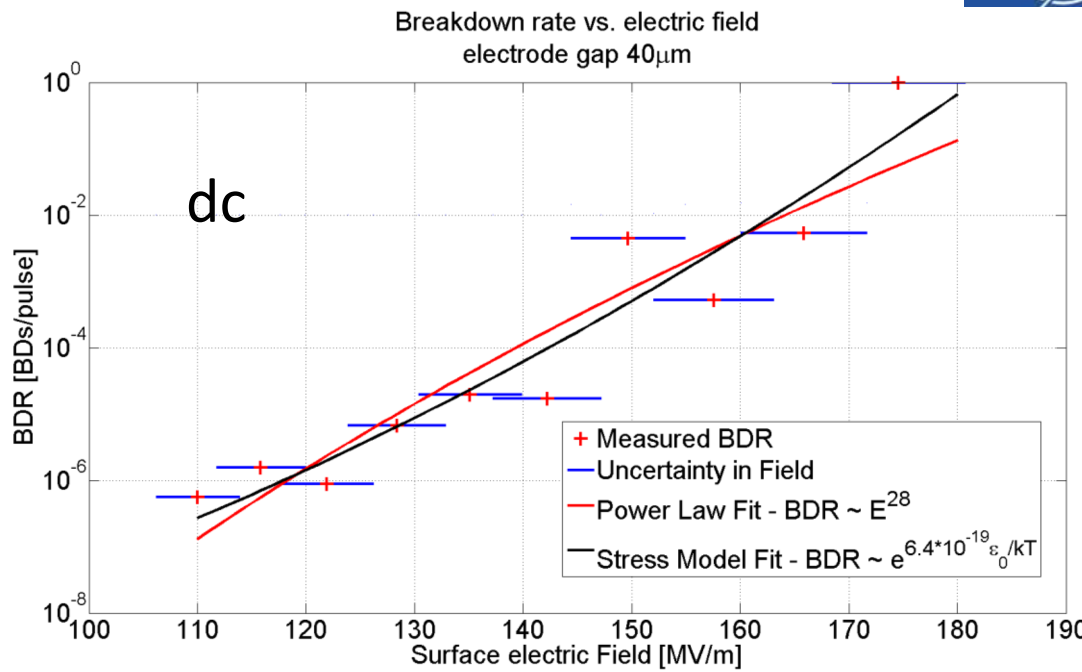
Theory and simulation – University of Helsinki, Hebrew University of Jerusalem and the University of Tartu

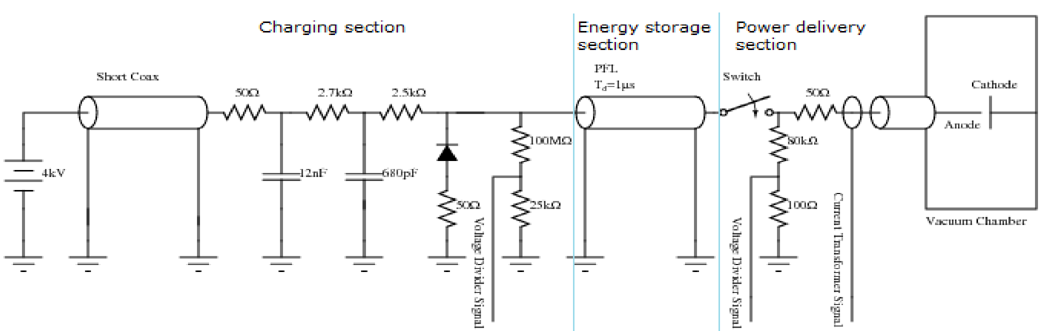
Experiment – high repetition rate pulsed dc systems at CERN

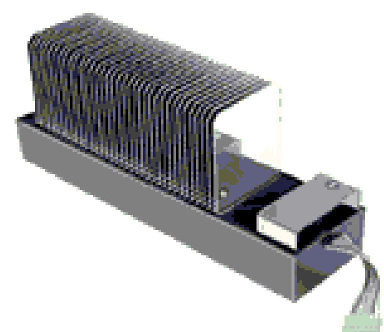


Pulse length dependence dc and rf



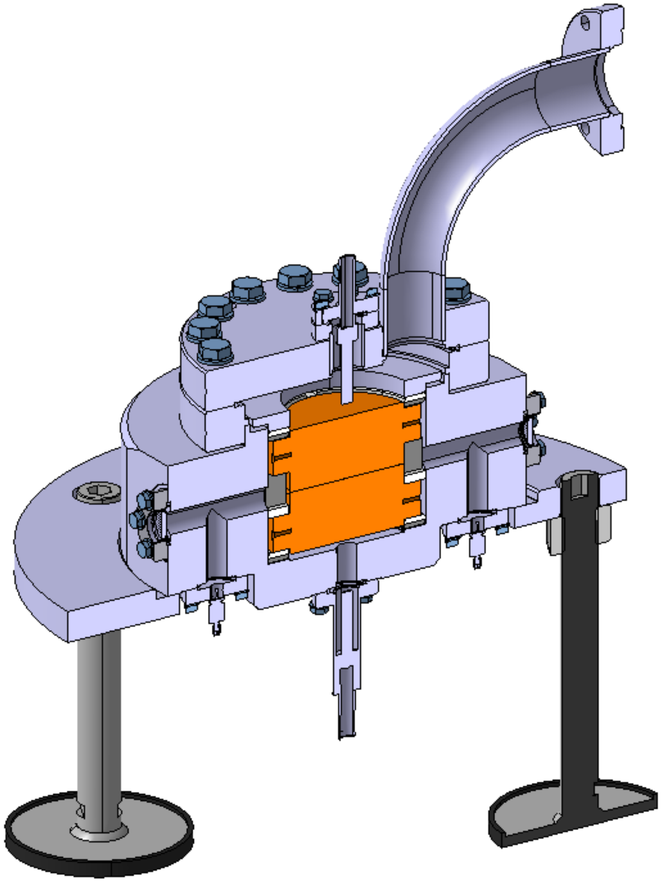


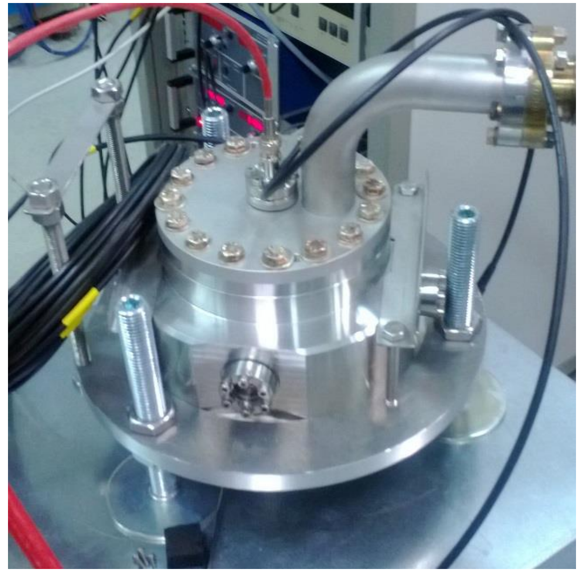


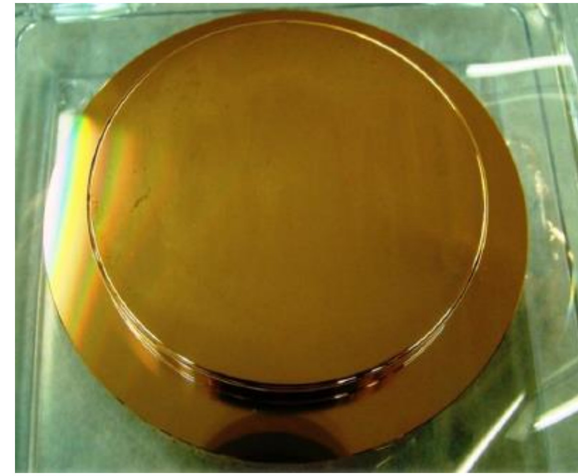


High repetition rate, 1kHz, MOSFET switch based high voltage pulser.

Large electrode system

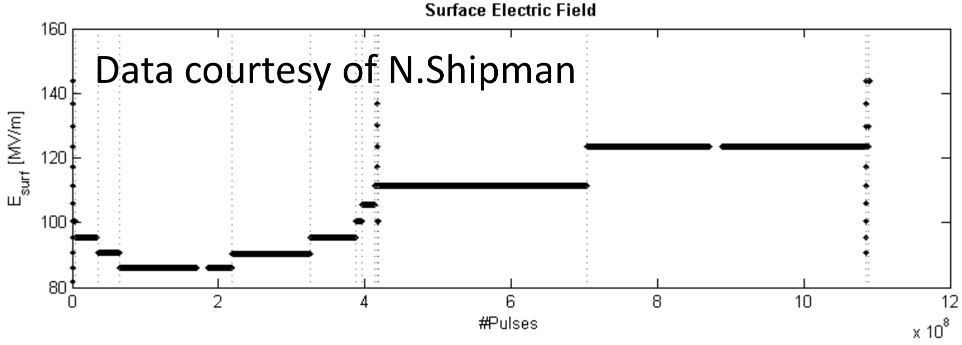


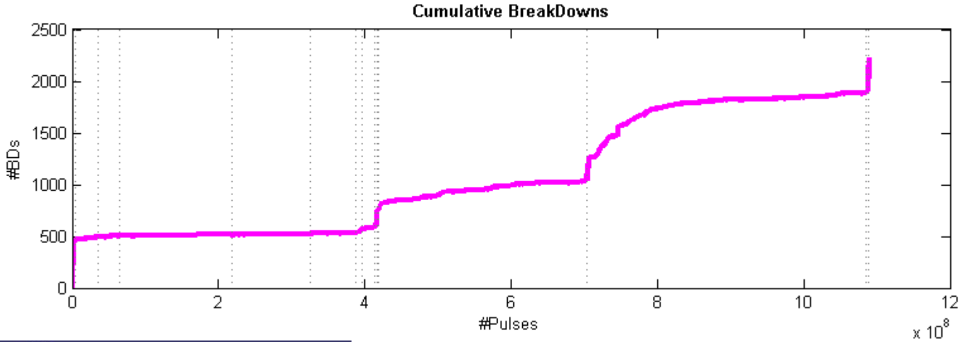




Standardized, simple, 62 mm diameter electrodes allow testing of materials and preparation procedures for basic studies and fabrication procedure optimization

High rep rate and large electrode system



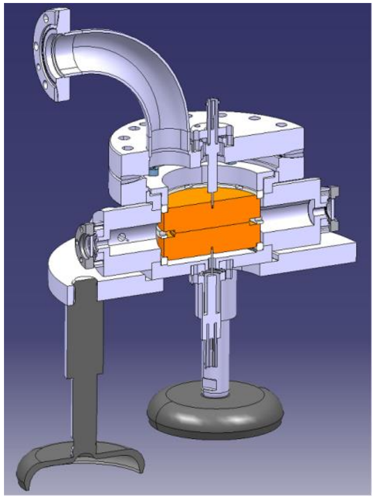


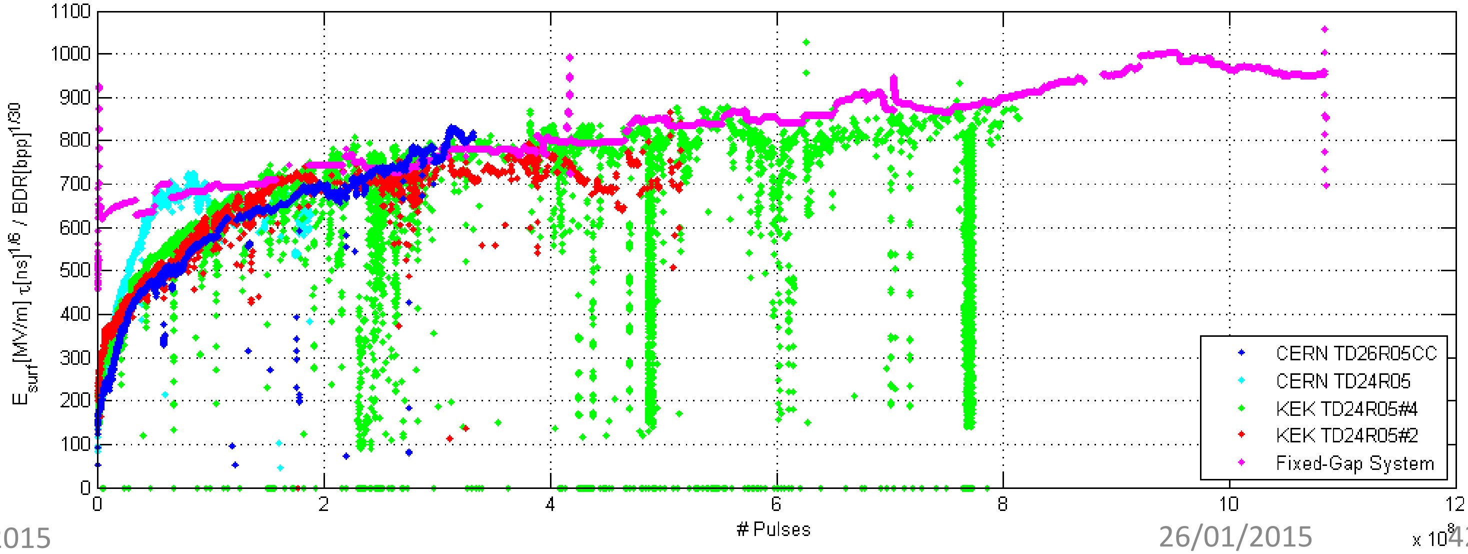
Long term behaviour remarkably similar to an rf cavity – conditioning and ultimate performance.

Much faster – x20

Much cheaper – x100

(approximately)



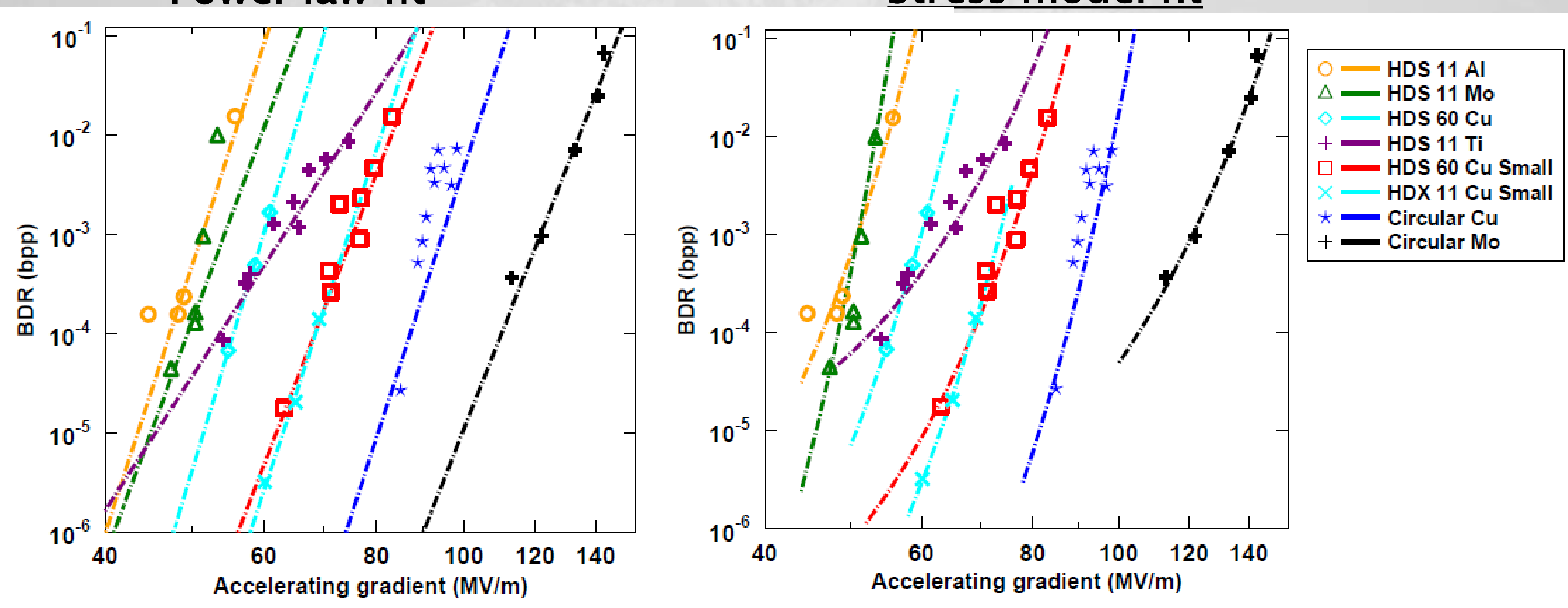


Dislocation-based model for electric field dependence

$$BDR \propto c = c_0 e^{-(E^f - \varepsilon_0 E^2 \Delta V)/kT} = c_0 e^{-E^f/kT} e^{\varepsilon_0 E^2 \Delta V / kT}$$

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

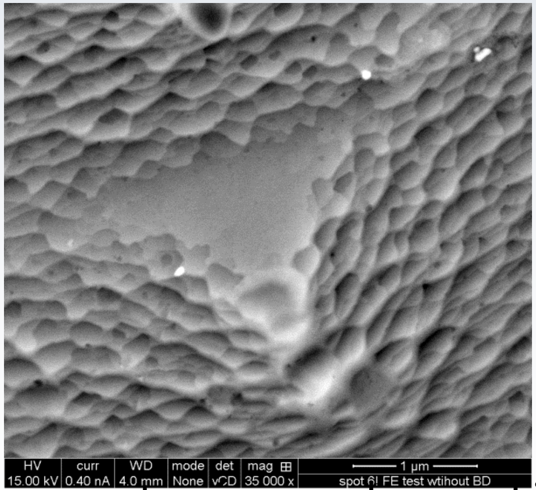
Power law fit | **Stress model fit**



[W. Wuensch, public presentation at the CTF3, available online at http://indico.cern.ch/conferenceDisplay.py?confId=8831.] with the model.]

Model

- Stochastic plastic model for breakdown formation:
  - BD caused by localized protrusions. These are formed due to dislocation activity within the sample resulting in protrusion growth.
  - The stochastic model, describes dislocation evolution leading to critical protrusion formation.
  - The sub breakdown population can be characterized through dark currents.
  - As it approaches the critical point – protrusion population increases leading to larger fluctuation in dark currents



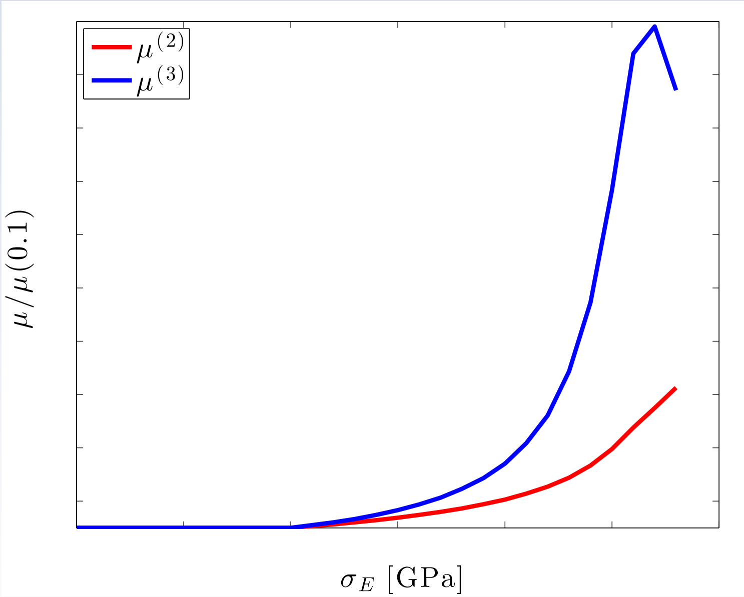
Surface protrusion as observed in the Field emission area of the DC sample.

Slide from Y. Ashkenazy

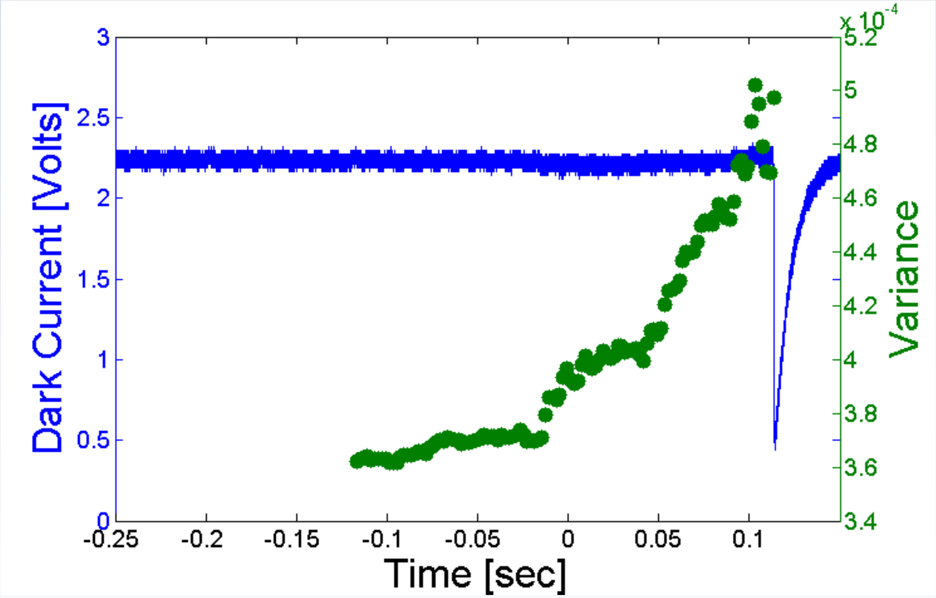
What are we looking for

- Model predicts strong fluctuations in observed current as the critical point is approached

Simulated 2nd and 3rd moment protrusion size and distribution vs driving force



Current as measured in an uncontrolled DC gap setup



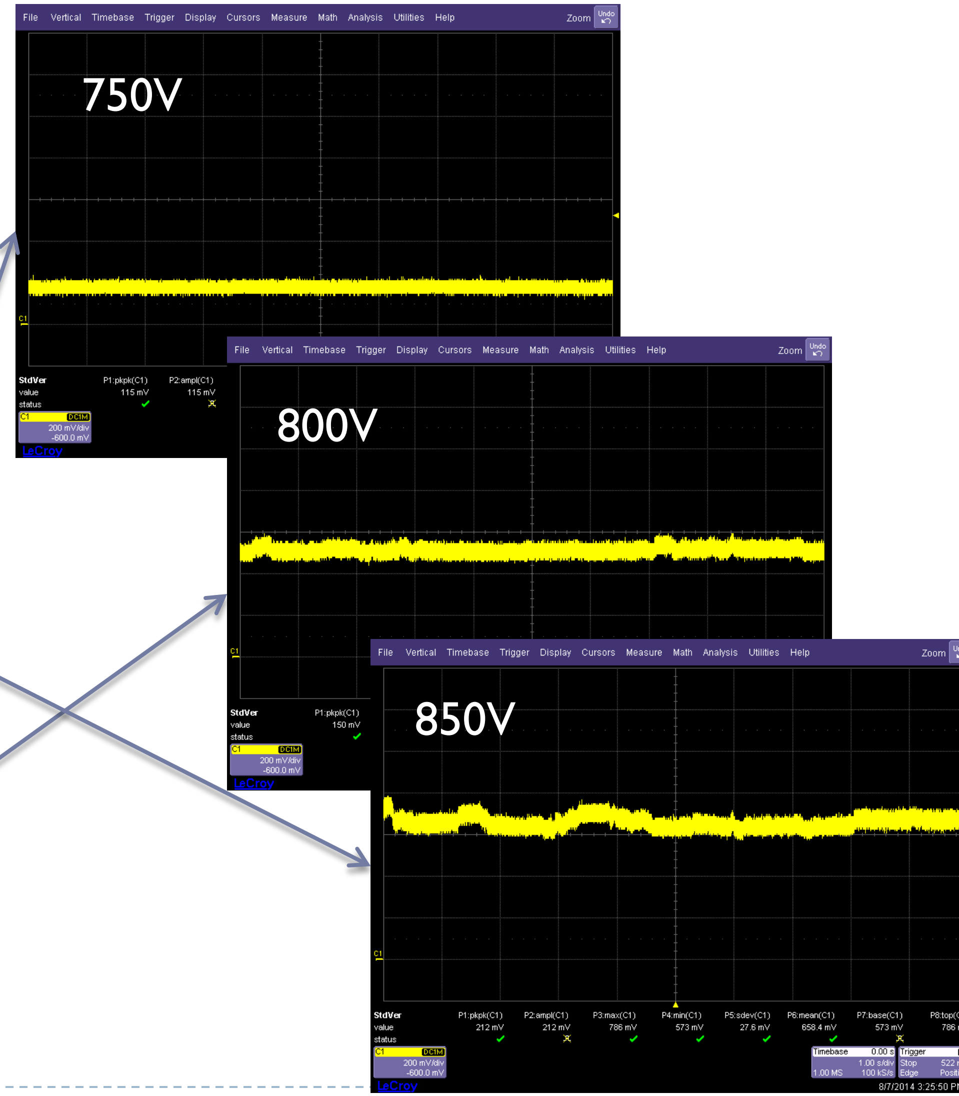
Proof of concept?

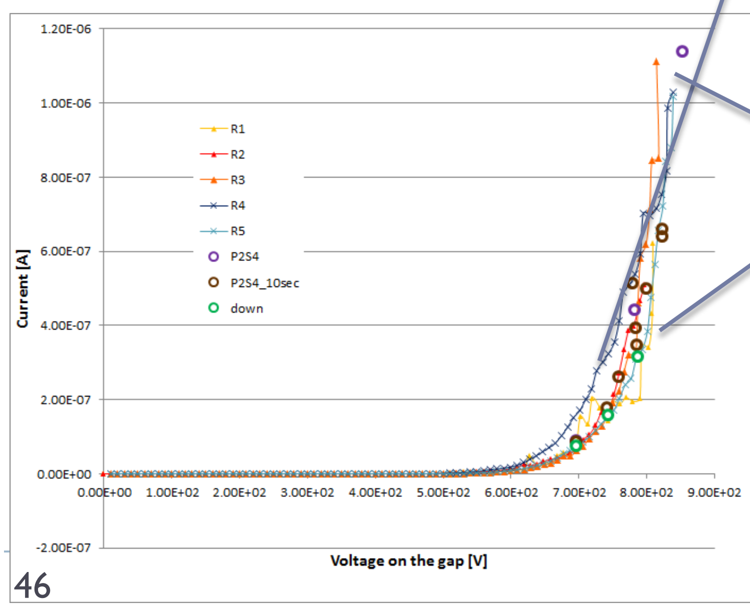
Uncontrolled gap, low I resolution,

Slide from Y. Ashkenazy

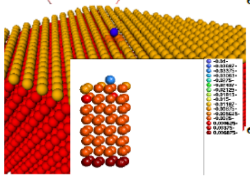
(Preliminary)
Current fluctuation measurements

- At higher field, higher average current & higher fluctuation were observed.
- Still need to improve current resolution.

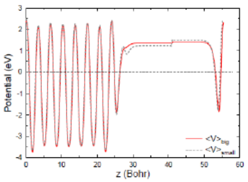




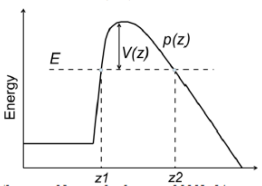
Electron current densities due to a surface adatom or step edge



- We estimate the difference in the electron current density due to the presence of an adatom or monoatomic steps on the surface.
- Zero-temperature current density is $J_{mo} = J_F D_F$
  - Here Z_F is effective incident current density and D_F is transition coefficient for tunneling probability calculated in Wentzel–Kramers–Brillouin (WKB) approximation as



$$D_F(E) = \frac{J_T}{J_F} = \frac{\exp\left(-\frac{2}{\hbar}\int_{z_1}^{z_2} dz\sqrt{2m_e(p(z)-E)}\right)}{J_F}$$



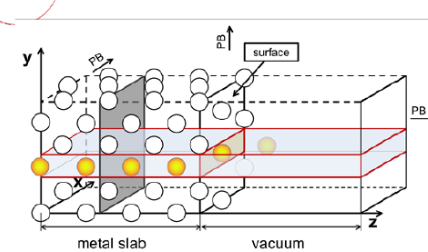
$$\frac{J_{ad}}{J_o} = \exp\left(-\frac{g_e}{2}\int_{z_1}^{z_2} dz\frac{\Delta p}{\sqrt{p_1(z)-E_F}}\right)$$

Field emission from surfaces with atomic level features

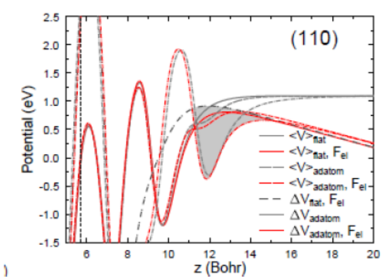
University of Helsinki

OIST, 5 March 2015

Effect of surface defect on FE

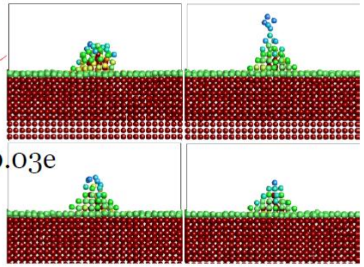


- We calculated J_{def}/J_o and found that for both types of surface defects – atomic steps and adatoms – and found that even such insignificant drop of the work function may cause the increase of the current density more than 50%



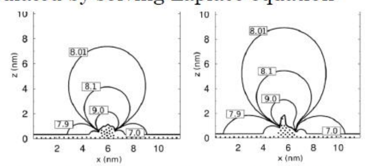
Face	100	110	111
Adatom	1.4	1.324	1.5
Step edge	1.64	1.36	1.74

Charges on surface atoms in MD



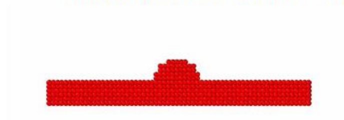
$q_{at} \leq 0.03e$

Distribution of the electric field is dynamically calculated by solving Laplace equation



Details in F. Djurabekova, S. Parviainen, A. Pohjonen and K. Nordlund, PRE 83, 026704 (2011).

- Charges on surface atoms are calculated by using our ***helmod*** code – hybrid ED-MD code, based on classical MD (molecular dynamics) code.
- The dynamics of atom charges follows the shape of electric field distortion on tips on the surface
- The atoms leave the tip as a result of evaporation enhanced by pulling effect from the external electric field.
  - No electromigration or interaction with electrons are



Flyura Djurabekova, HIP, University of Helsinki @ CLIC workshop, 2015, CERN -- Jan. 28, 2015 6

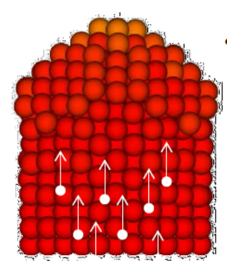
Dynamics of atomic level features under influence of high surace electric fields

University of Helsinki

OIST, 5 March 2015

Electromigration (EM) in MD

- Implemented as additional ”electron wind force” acting on atoms in protrusion as in Bly et al. [PhysRevB.53 (1995)13909]
- Force proportional to the internal electric field and effective charge of copper atoms as seen by current

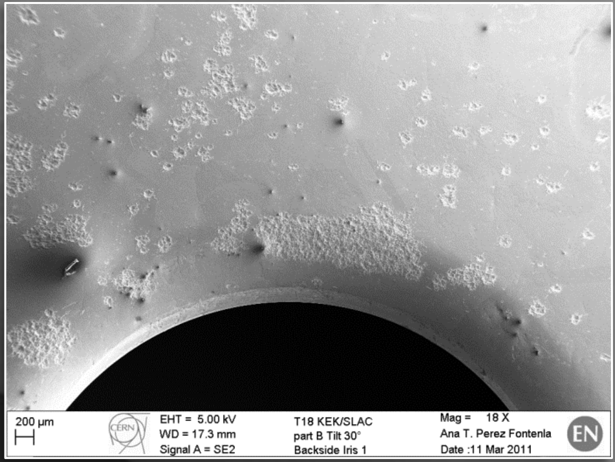


$$F = E_{\text{int}} Z_{eff} \qquad E_{\text{int}} = J_{GTF} / \sigma \qquad Z_{eff} \approx \sout{10}\ 40$$

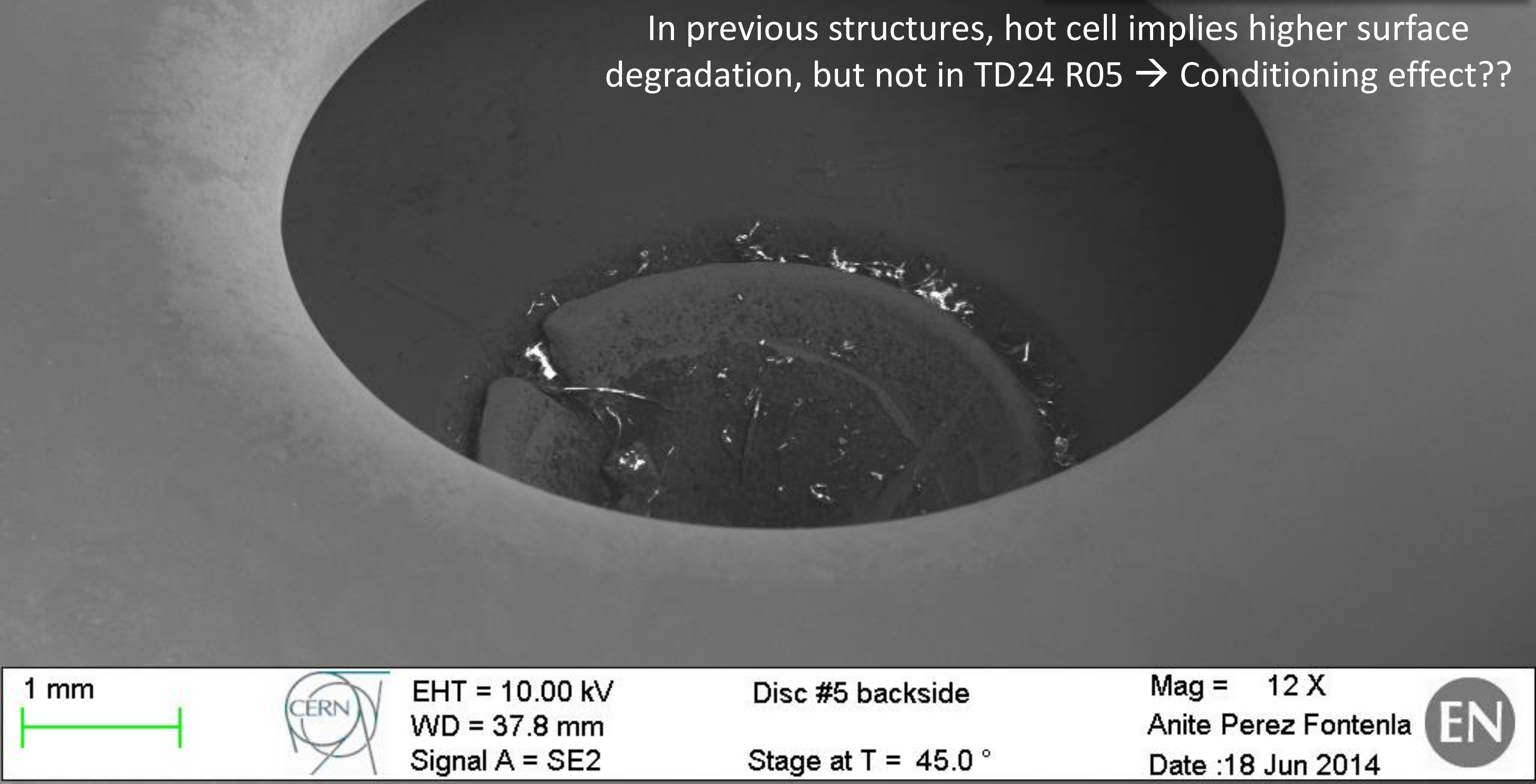
- Assume current (and force) is going straight upwards
- Assume effective charge $Z_{\text{eff is constant}}$

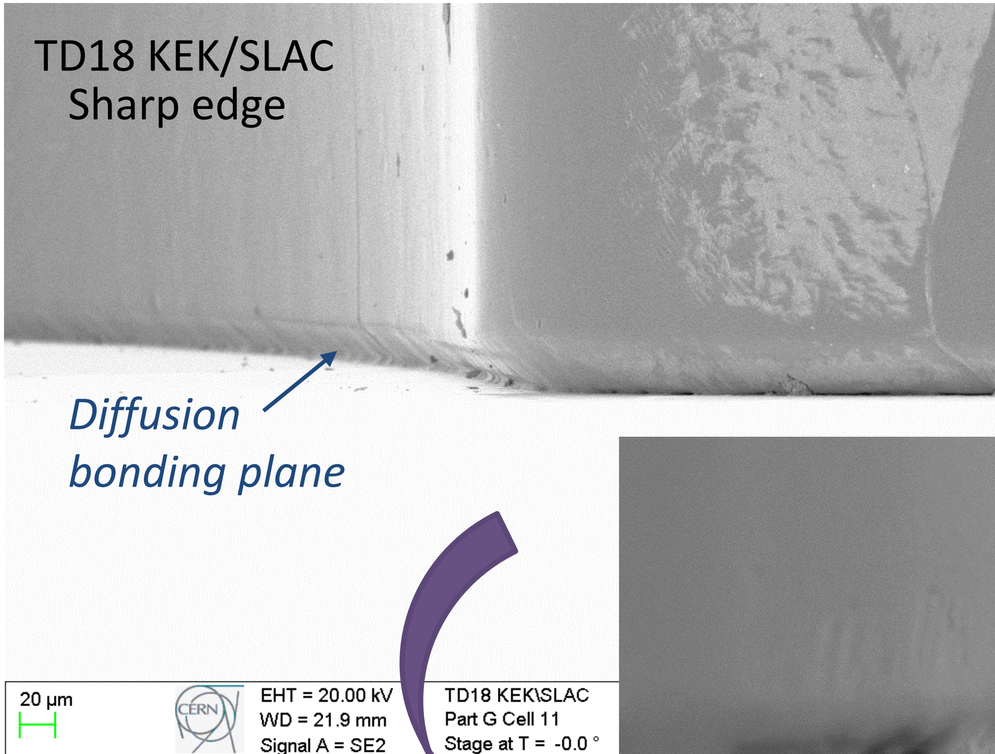
What does a hot cell look like?

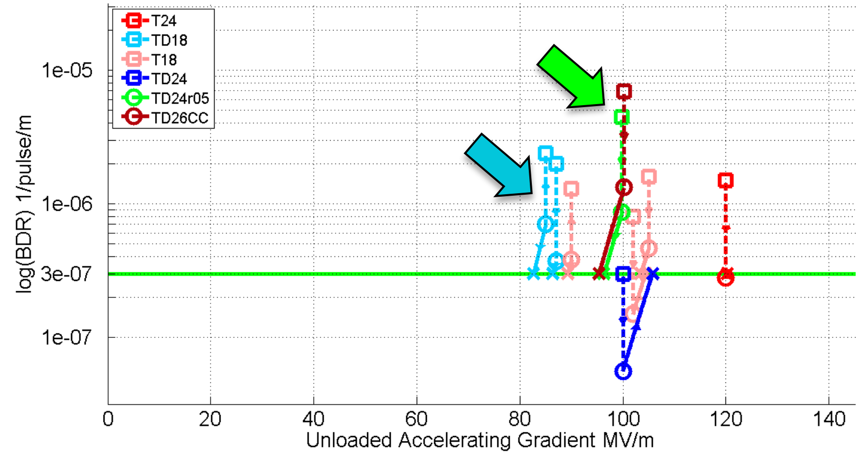
US cell #5_Example of the general aspect of the iris region

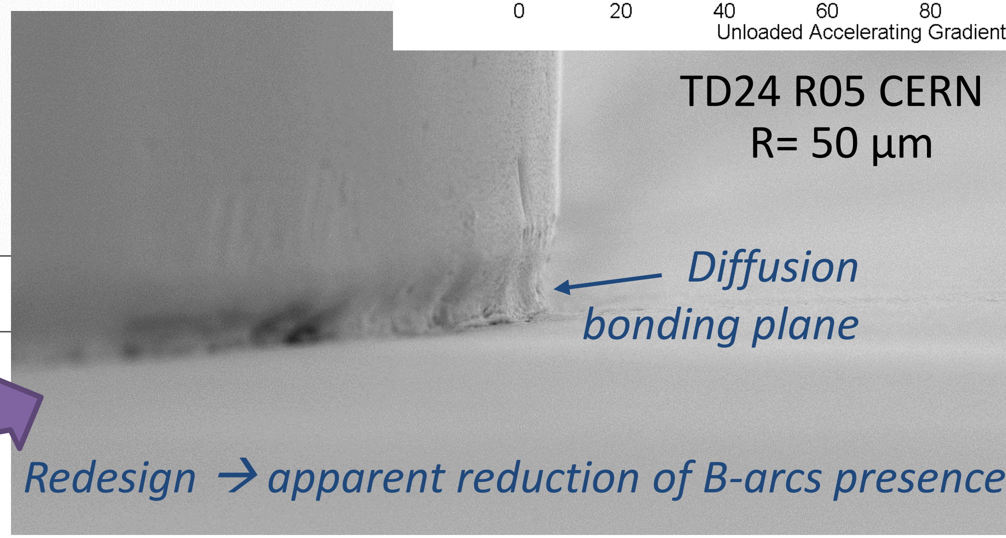


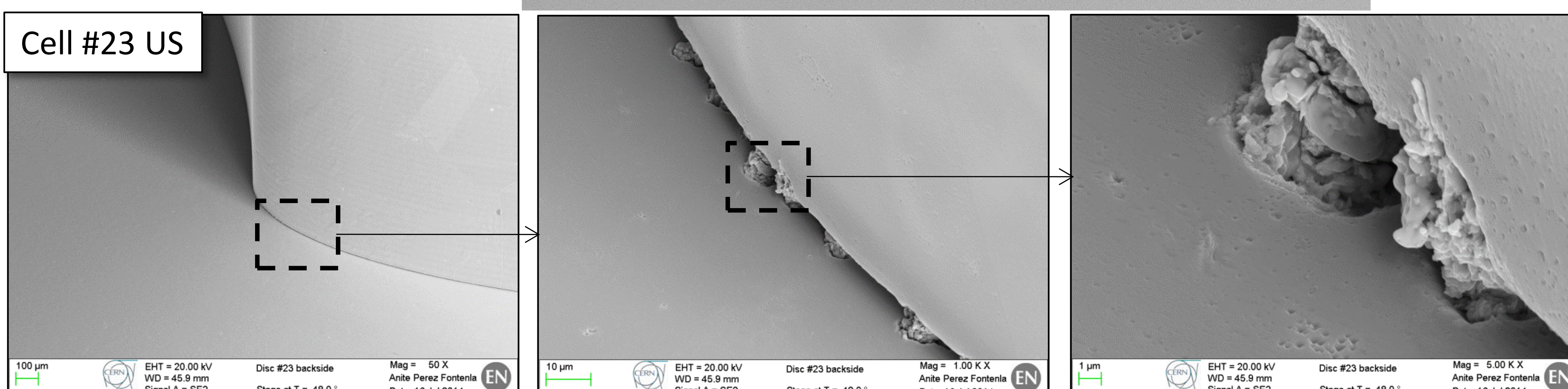
In previous structures, hot cell implies higher surface degradation, but not in TD24 R05 → Conditioning effect??



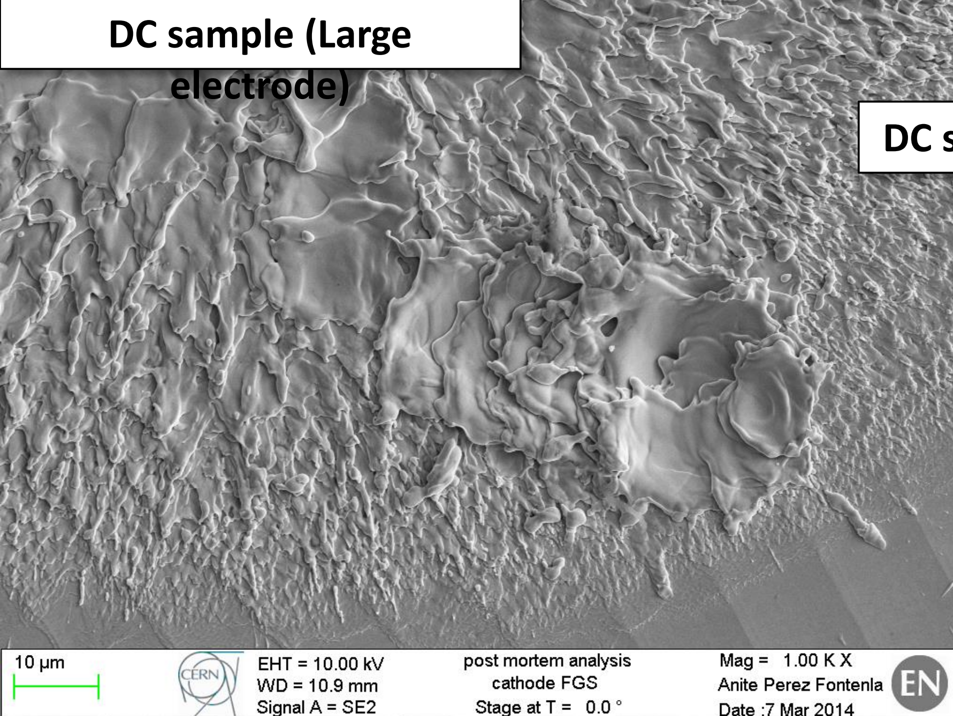

TD18 KEK/SLAC
Sharp edge
Diffusion
bonding plane
20 µm
EHT = 20.00 kV
WD = 21.9 mm
Signal A = SE2
TD18 KEK\SLAC
Part G Cell 11
Stage at T = -0.0 °


T24
TD18
T18
TD24
TD24r05
TD26CC
log(BDR) 1/pulse/m
1e-05
1e-06
3e-07
1e-07
0
20
40
60
80
100
120
140
Unloaded Accelerating Gradient MV/m

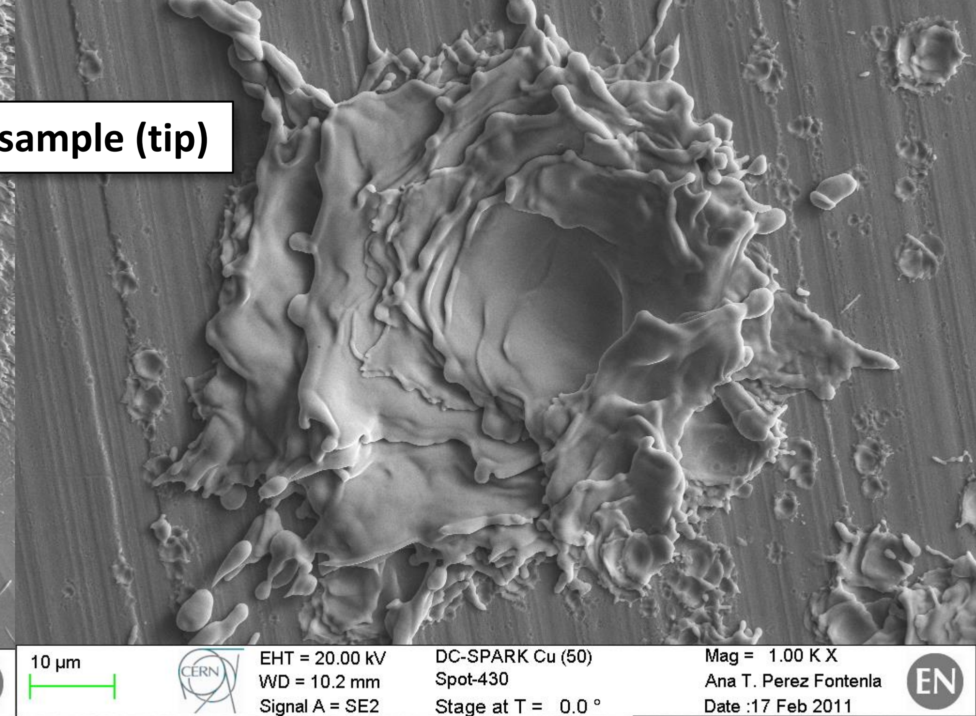

TD24 R05 CERN
R= 50 µm
Diffusion
bonding plane
Redesign → apparent reduction of B-arcs presence


Cell #23 US
100 µm
EHT = 20.00 kV
WD = 45.9 mm
Signal A = SE2
Disc #23 backside
Stage at T = 48.0 °
Mag = 50 X
Anite Perez Fontenla
Date :16 Jul 2014
10 µm
EHT = 20.00 kV
WD = 45.9 mm
Signal A = SE2
Disc #23 backside
Stage at T = 48.0 °
Mag = 1.00 K X
Anite Perez Fontenla
Date :16 Jul 2014
1 µm
EHT = 20.00 kV
WD = 45.9 mm
Signal A = SE2
Disc #23 backside
Stage at T = 48.0 °
Mag = 5.00 K X
Anite Perez Fontenla
Date :16 Jul 2014

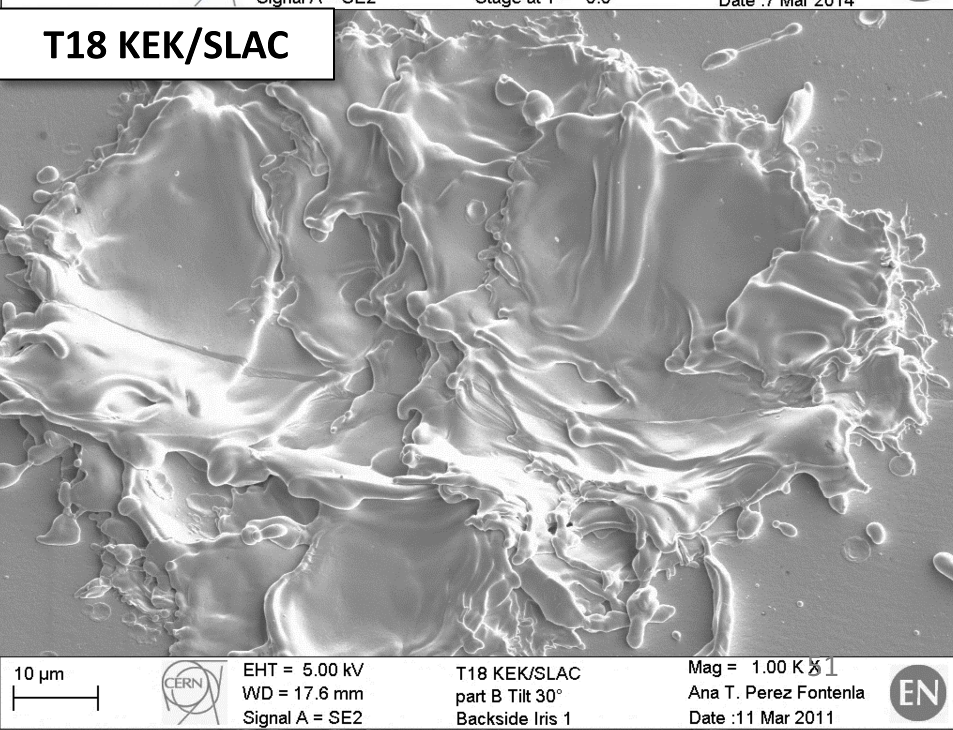
DC sample (Large electrode)



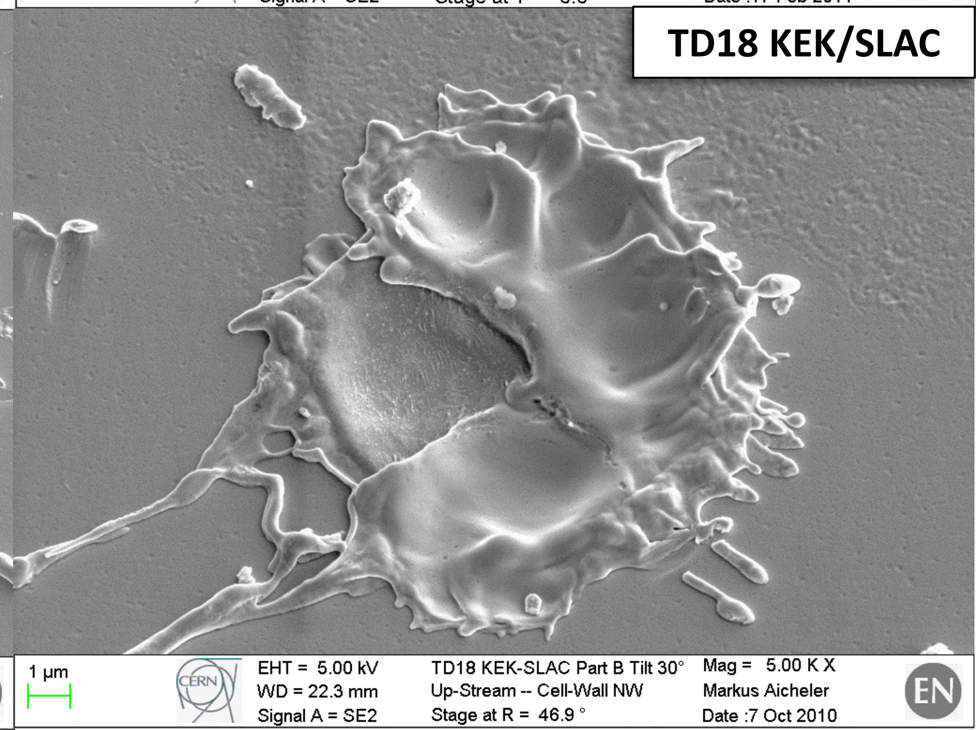
DC sample (tip)

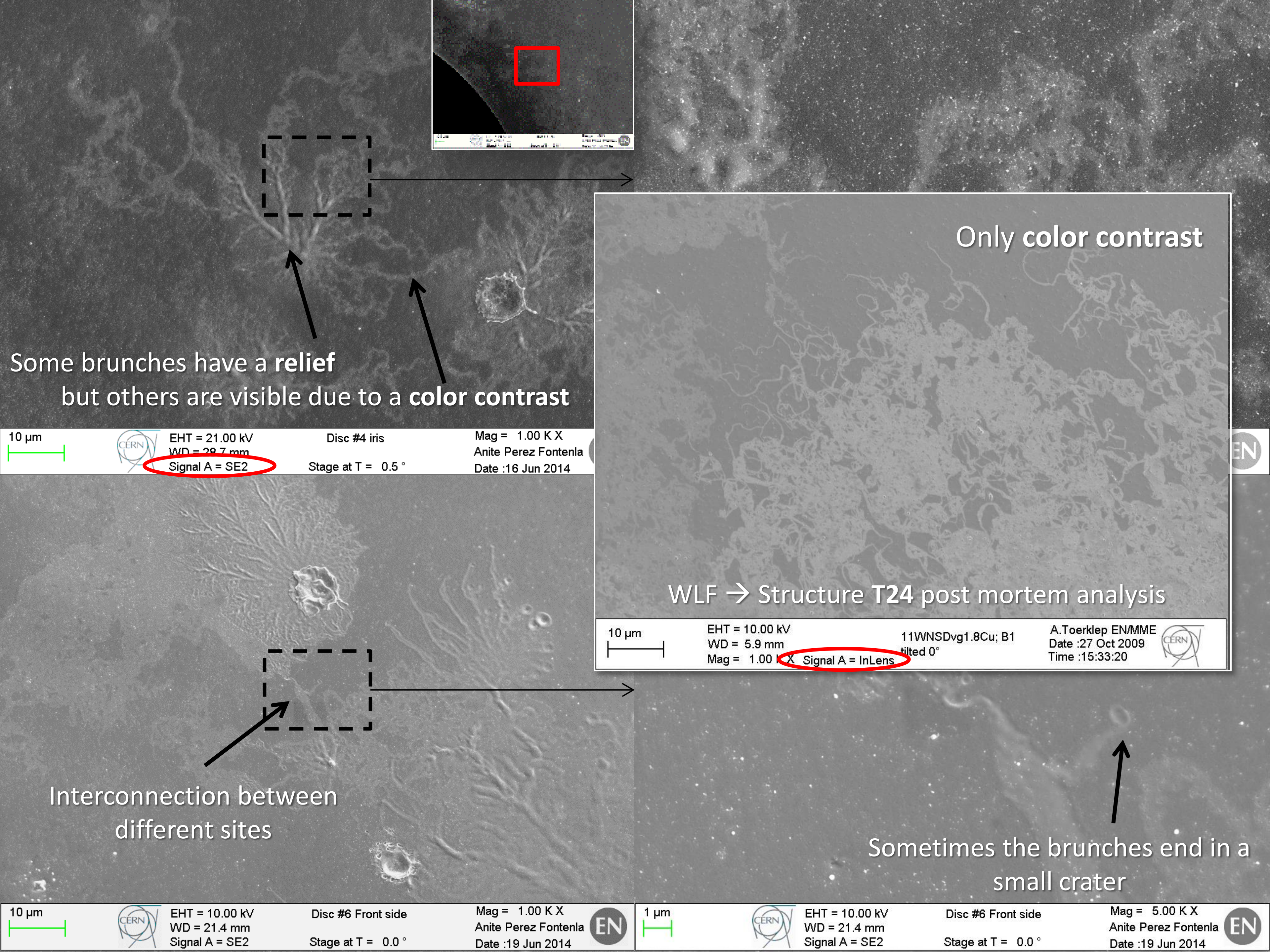


T18 KEK/SLAC



TD18 KEK/SLAC




Some brunches have a **relief**
but others are visible due to a **color contrast**
10 µm
EHT = 21.00 kV
WD = 28.7 mm
Signal A = SE2
Disc #4 iris
Stage at T = 0.5 °
Mag = 1.00 K X
Anite Perez Fontenla
Date :16 Jun 2014
Only **color contrast**
WLF → Structure **T24** post mortem analysis
10 µm
EHT = 10.00 kV
WD = 5.9 mm
Mag = 1.00 K X
Signal A = InLens
11WNSDvg1.8Cu; B1
tilted 0°
A.Toerklep EN/MME
Date :27 Oct 2009
Time :15:33:20
Interconnection between
different sites
10 µm
EHT = 10.00 kV
WD = 21.4 mm
Signal A = SE2
Disc #6 Front side
Stage at T = 0.0 °
Mag = 1.00 K X
Anite Perez Fontenla
Date :19 Jun 2014
Sometimes the brunches end in a
small crater
1 µm
EHT = 10.00 kV
WD = 21.4 mm
Signal A = SE2
Disc #6 Front side
Stage at T = 0.0 °
Mag = 5.00 K X
Anite Perez Fontenla
Date :19 Jun 2014

Conclusions

- The CLIC project has fixed it's initial energy stage at 380 GeV. The baseline designs at this initial and 3 TeV energies are being updated. We eagerly await LHC run 2.
- Accelerating structures routinely operate in the range of 100 MeV and a large increase in manufacturing and testing capability is underway.
- We actively work with other applications of X-band and high-gradient technology.
- Significant advances in the understanding of high surface fields are being made.
- **I sincerely hope that we can identify collaboration subjects!**

Upcoming events

Mechanisms of Vacuum Arcs-5

MeVArc

2-4 September, 2015

The Hebrew University of Jerusalem

Sandia National Laboratories

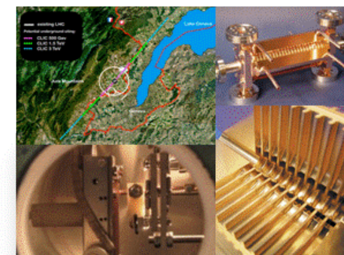
The workshop aims to combine the efforts of researchers in different fields to understand the mechanisms underlying the highly intriguing phenomenon of electrical breakdown. The workshop will cover rf and dc types of electrical breakdowns, including theory, experiment, and simulation. The workshop will be preceded by a half-day mini-school on modeling surface (electrode) evolution processes relevant to electrical breakdown phenomena.

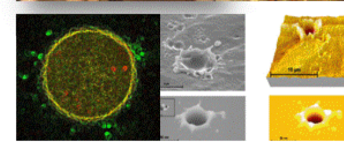
Topics

Experiments: vacuum arcs, dc spark systems, rf accelerating structures, materials, diagnostics, techniques and technologies for high gradients, and arcing in fusion devices.

Theory and simulations: surface modification under electric and electromagnetic fields, PIC and PIC-DSMC plasma simulations, dislocation activity, plasma-wall interactions, and surface damage and evolution.

Applications: particle accelerators, discharge-based devices, electrostatic failure mitigation, fusion devices, satellites and other industrial interests.





Venue

The workshop will be held in Saariselkä, Lapland. Lappish ruska is the time of beautiful autumn colors.

Organizers

Flyura Djurabekova
HIP, University of Helsinki, Finland

Walter Wuensch, Sergio Calatroni
CERN, Switzerland

Matthew Hopkins
Sandia National Laboratories, USA

Yinon Ashkenazy
Hebrew University of Jerusalem, Israel

http://indico.cern.ch/conferenceDisplay.py?confId=246618