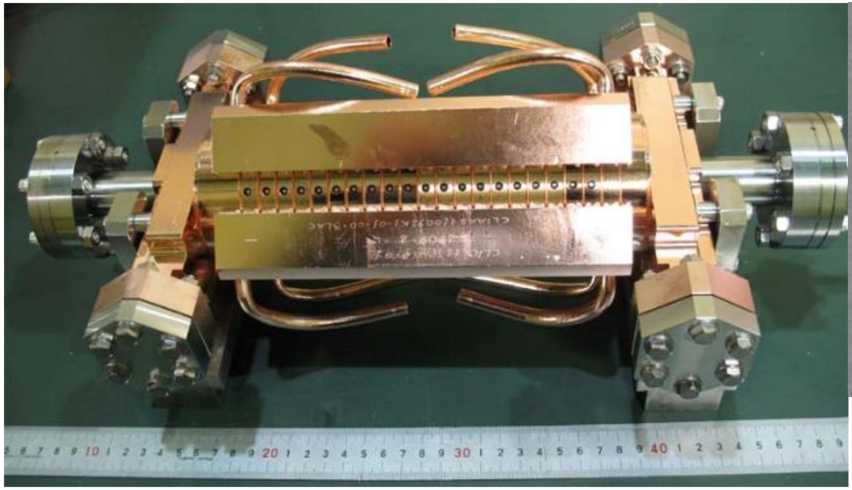
High-Gradient Acceleration: CLIC and Beyond

Introduction

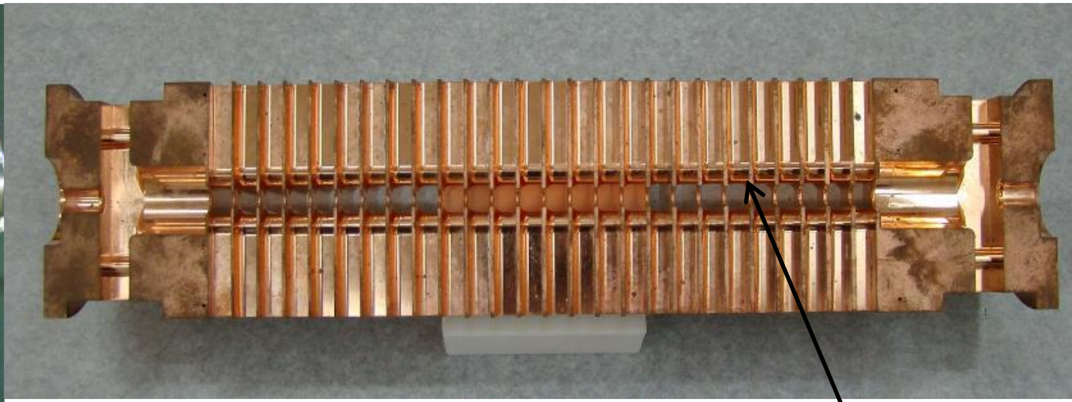
CLIC's goal of multi-TeV lepton physics relies on achieving 100 MV/m-range accelerating gradient.

- Update on achieved accelerating structure and test facility performances .
- Overview of other applications of high-gradient and X-band technology.

Accelerating structure



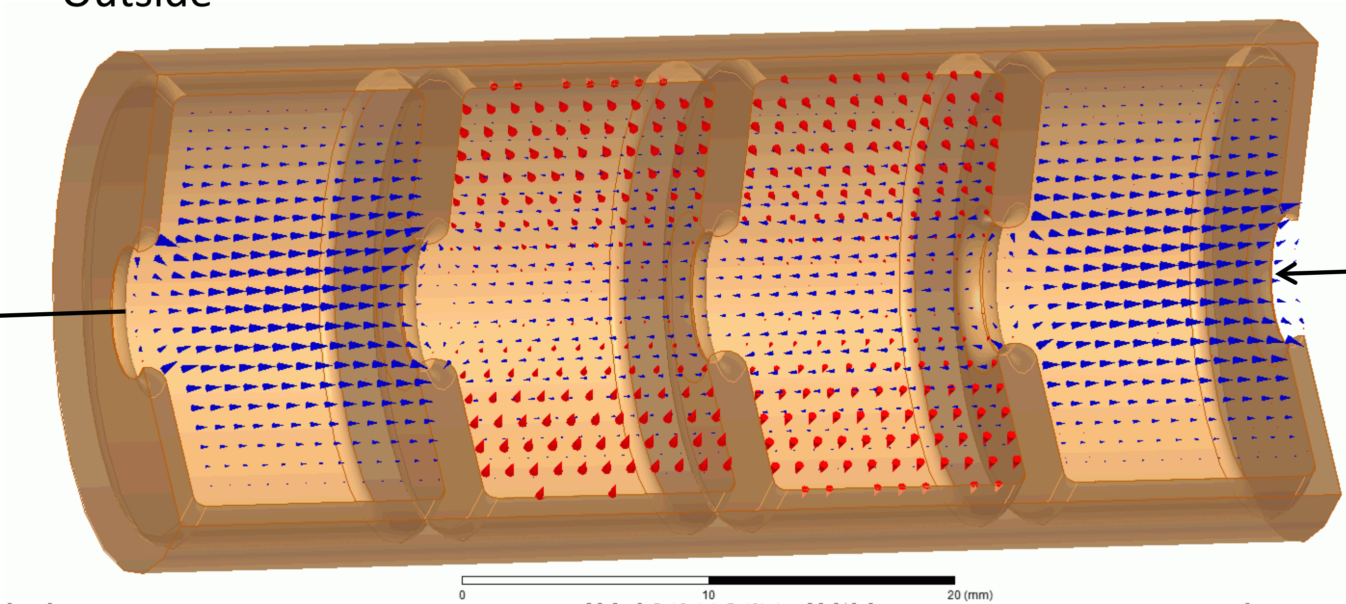
Outside



Inside

11.994 GHz X-band

6 mm diameter beam aperture



beam propagation direction

Concept

Basic terminology

CLIC accelerating structure specifications include:

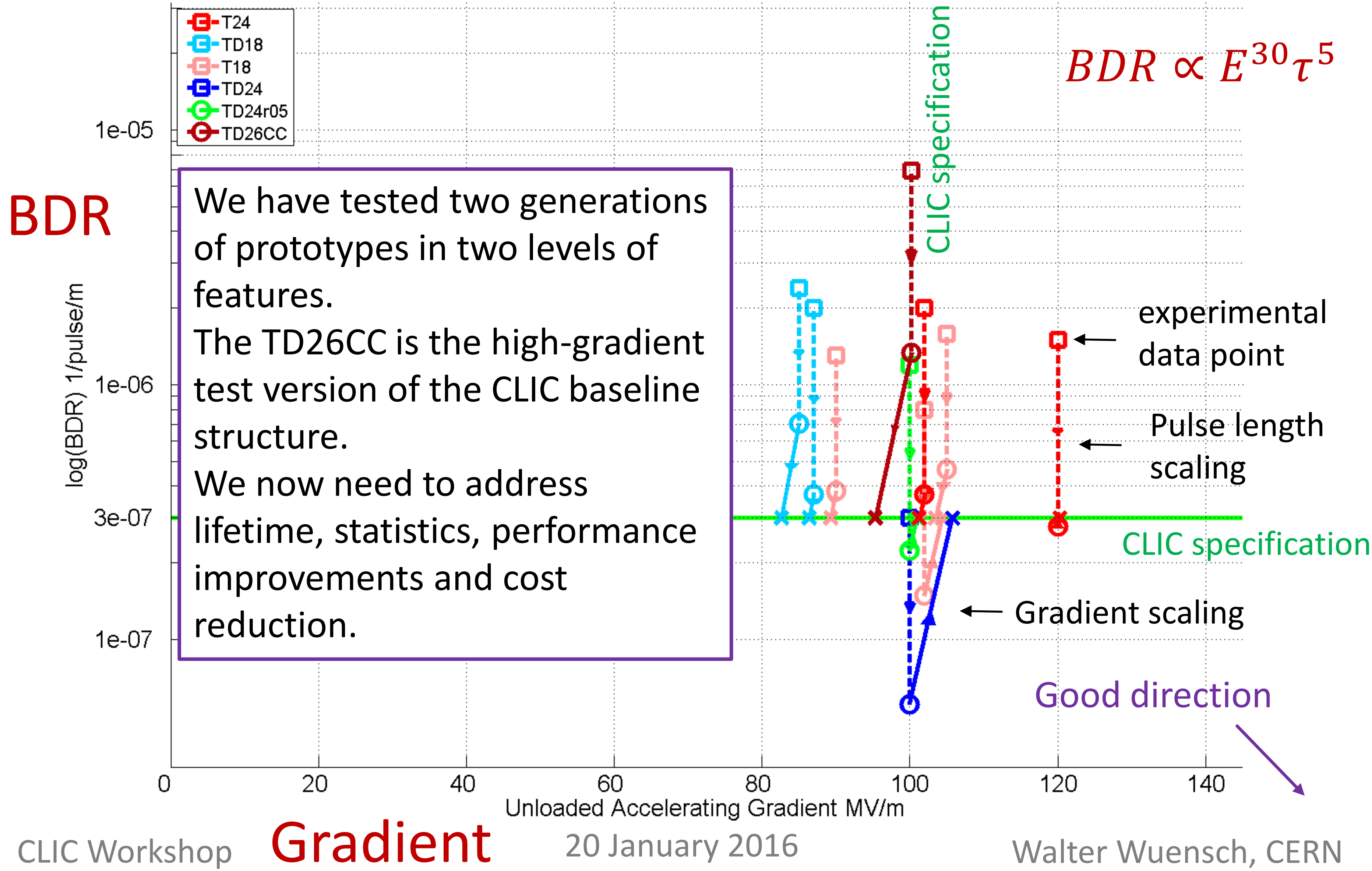
- a gradient 100 MV/m,
- a pulse length 180 ns,
- and breakdown rate 3×10^{-7}1/pulse/m.

The breakdown rate, *BDR*, is the fraction of pulses which have a vacuum arc, also called a breakdown – important because the breakdown currents and lost acceleration result in lost luminosity on that pulse.

$$\mathcal{L} = H_D \frac{N^2}{4\pi\sigma_x\sigma_y} n_b f_r$$

The three specs are related to each other: $BDR \propto E^{30}\tau^{5}$

The story up to now

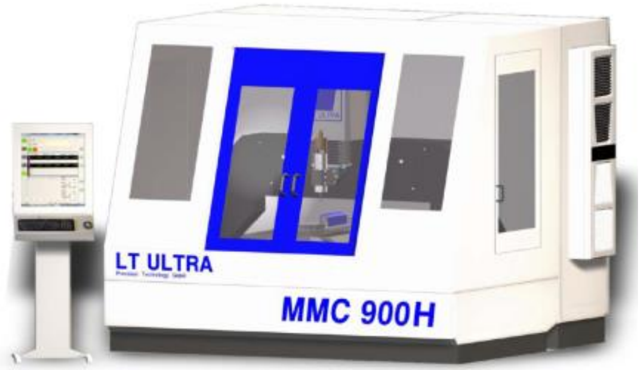


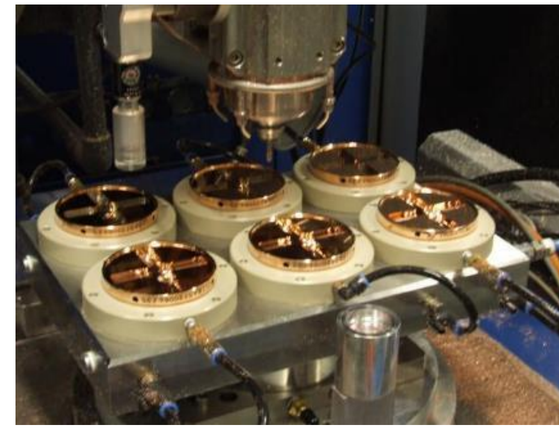
We have tested two generations of prototypes in two levels of features.
The TD26CC is the high-gradient test version of the CLIC baseline structure.
We now need to address lifetime, statistics, performance improvements and cost reduction.

Manufacture and test

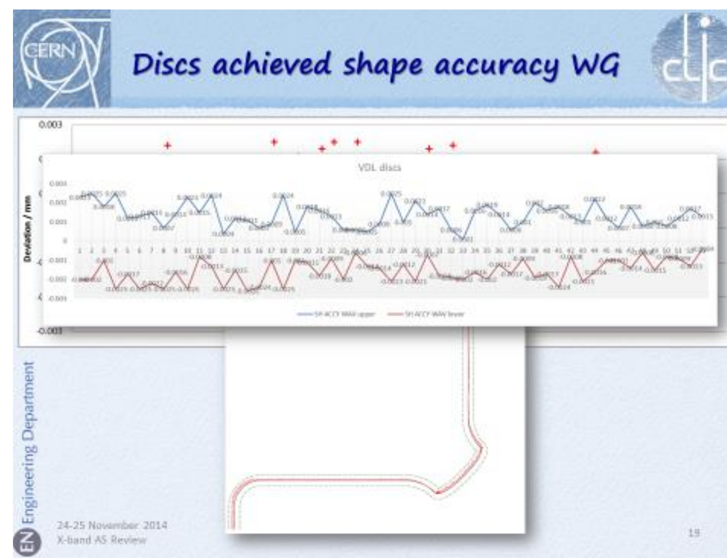
Commercial micron-precision machining

S. Atieh, A. Solodko





Micron-precision turning and milling.

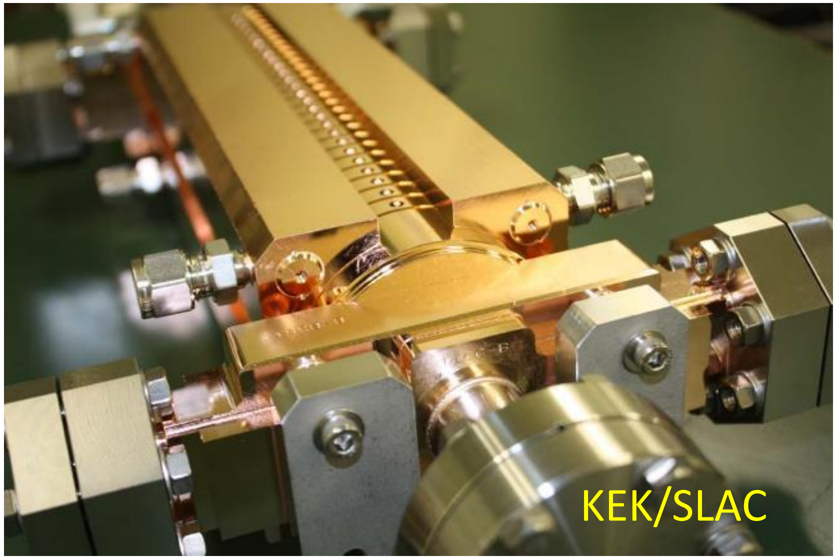


High-gradients, high-frequencies and tight mechanical tolerances go together.

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

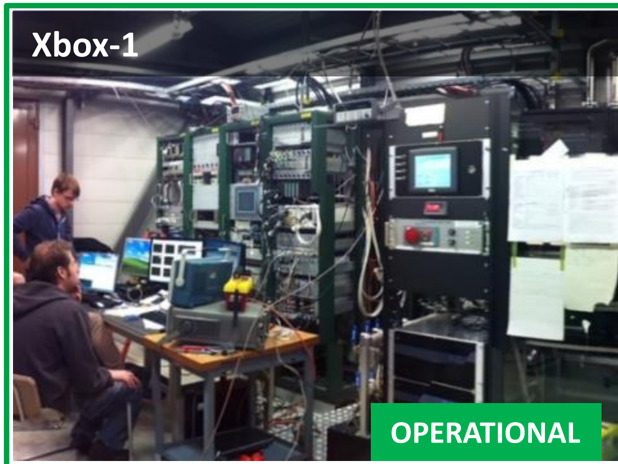
Assembly

T. Higo



J. Shi

Testing Capability at CERN



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)

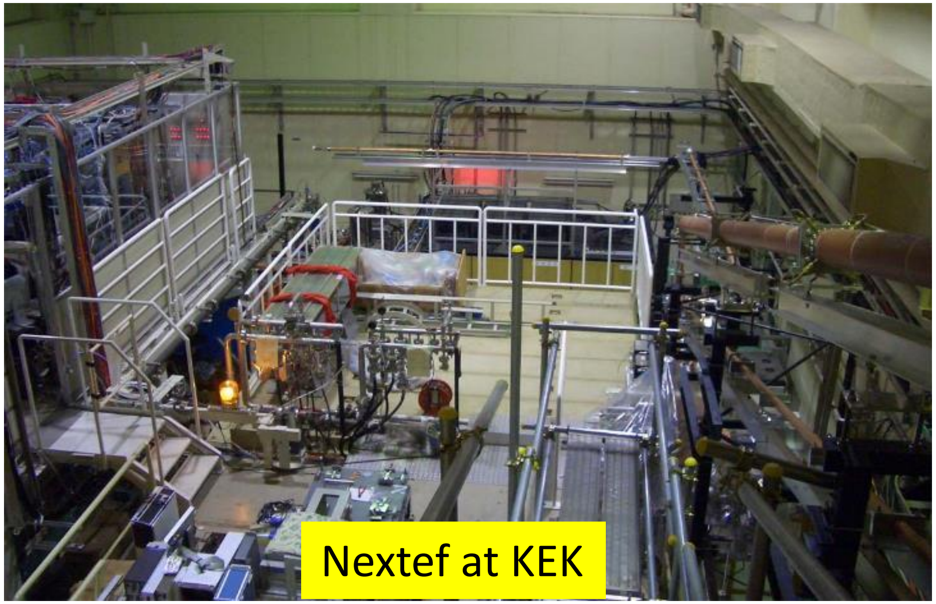
Xbox-3B/C/D: COMMISSIONING

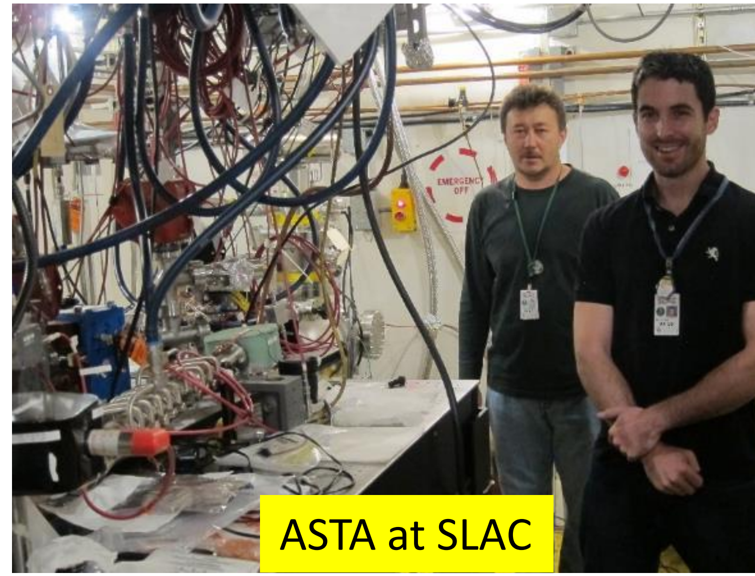
4x Toshiba 6MW 5us klystron
4x Scandinova Modulators
Rep Rate 400Hz

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

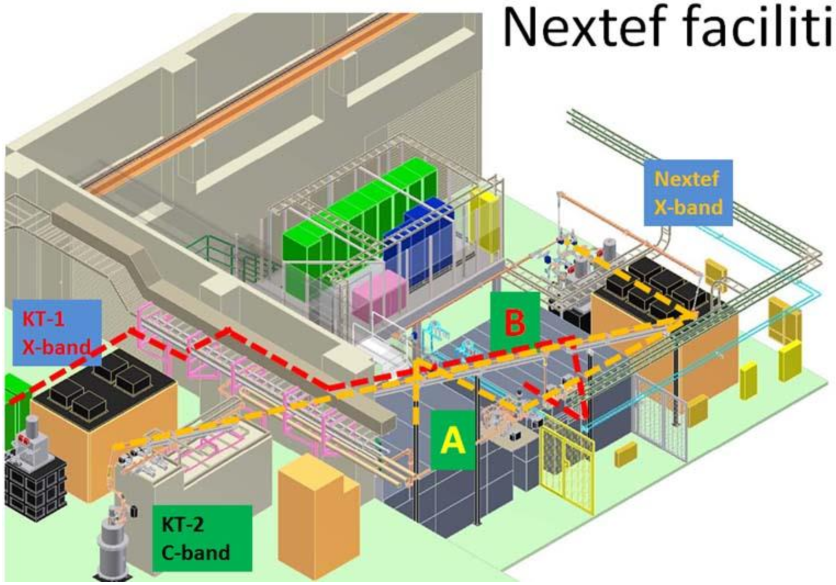
Medium power test:
3D printed Ti waveguide (Xbox-3A)

X-band test stands at KEK and SLAC





Nextef facilities



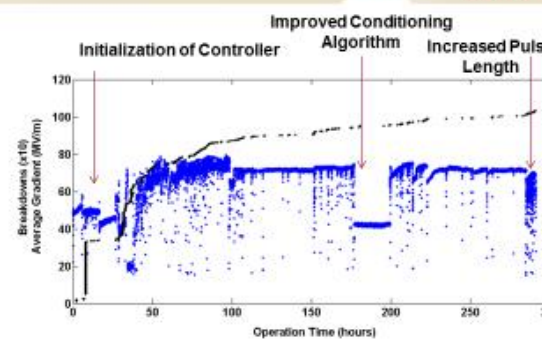
SLAC: CLIC Structure Conditioning

Xbox II Architecture

SLAC

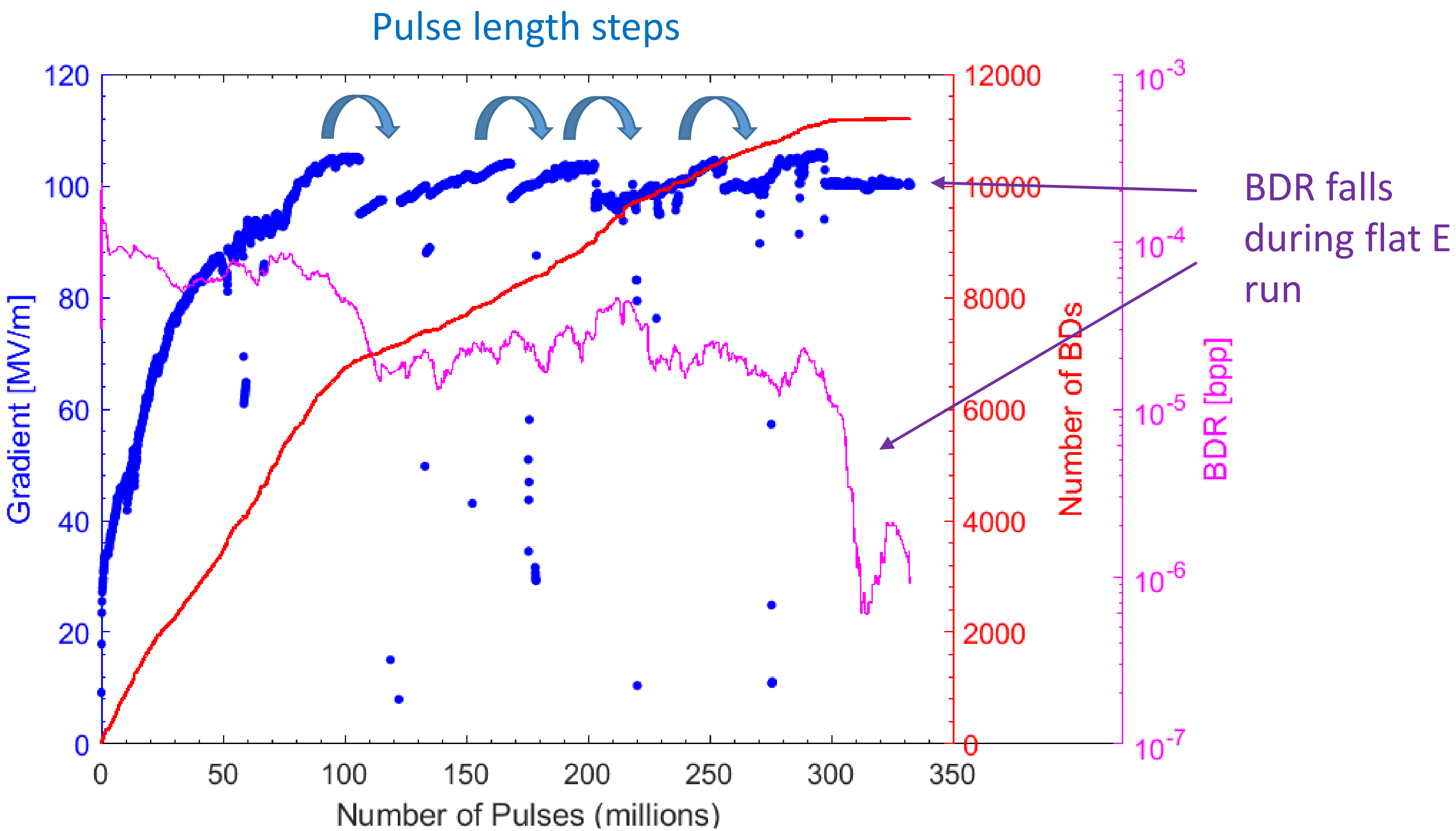
Status:

- All computation functionality in place
- Operating at 25 MW, 75 MV/m
  - Pulse length 200ns
- Approximately 300 operational hours
- 600+ operational breakdowns
- 65 million pulses



Conditioning

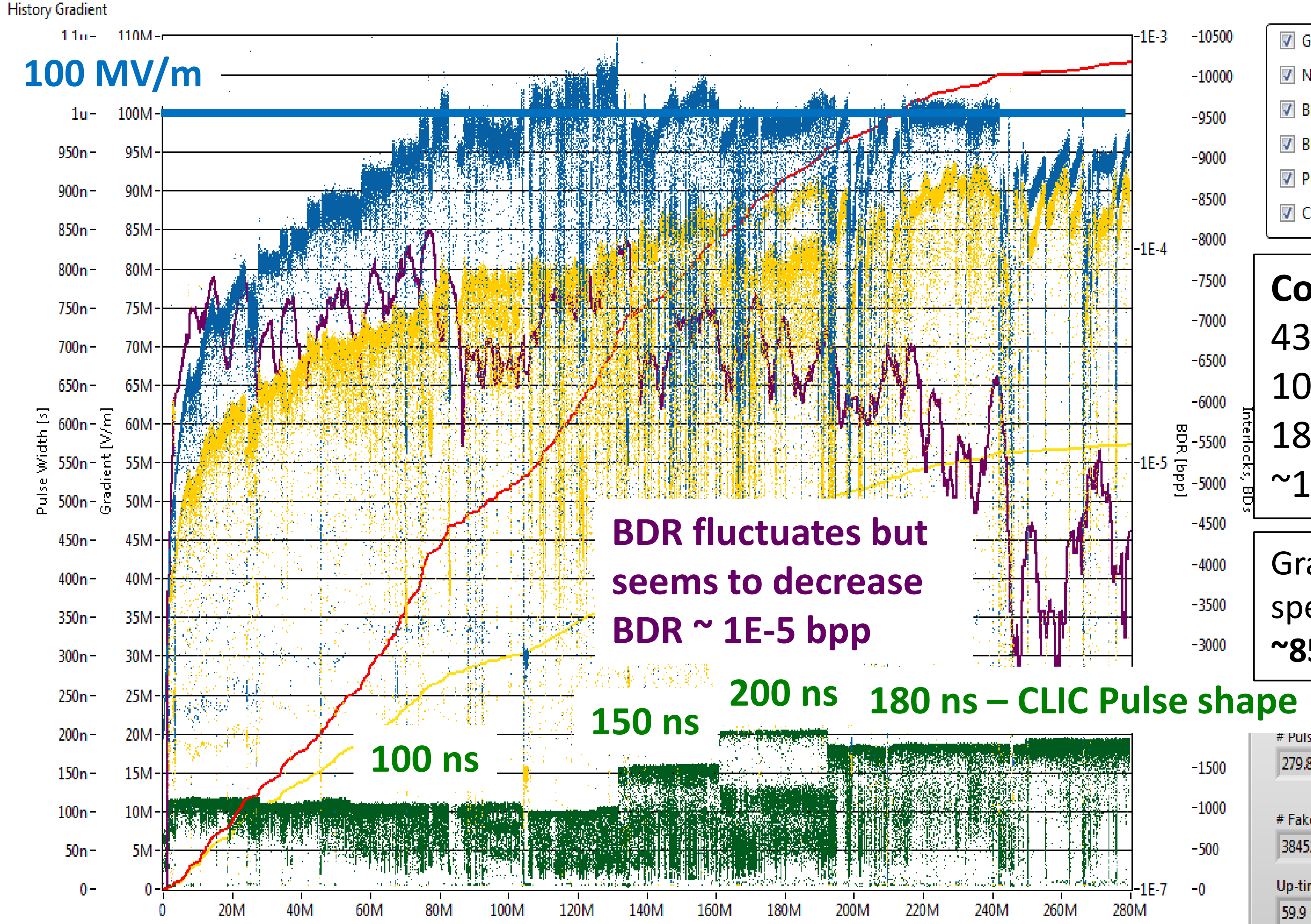
Accelerating structures do not run right away at full specification – pulse length and gradient need to be gradually increased while pulsing. Typical behaviour looks like this:



4 million pulses per day at 50 Hz

Ongoing tests

Xbox-1/Dogleg: TD26CC_N1 - full history

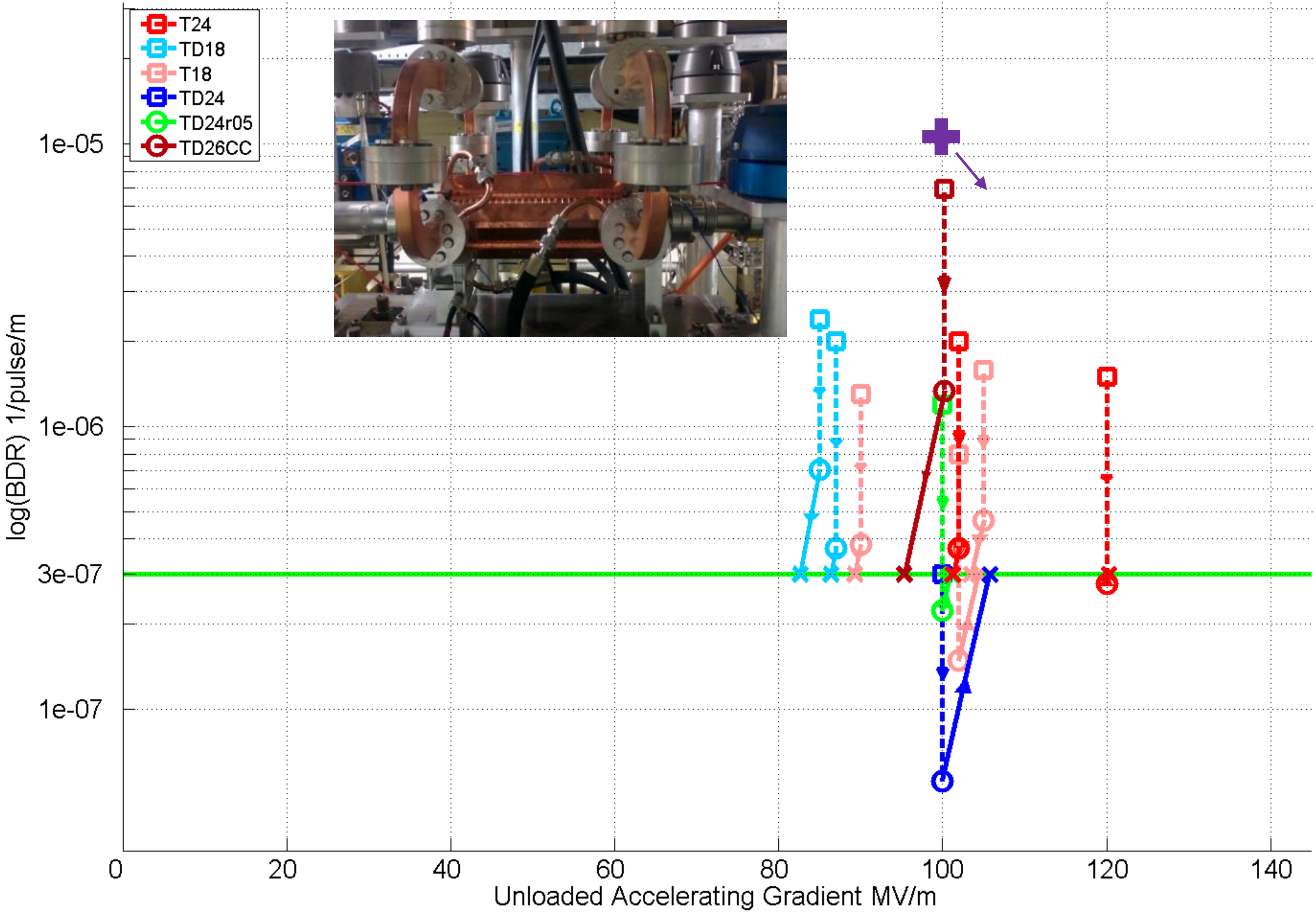


Conditioning status:
43.3 MW
100MV/m
180ns
~1e-5bpp

Gradient at CLIC pulse specs:
~85MV/m

# Pulses	Equiv hours @50Hz	Run hours
279.8M	1555	2594.41
# Fake BDs	**# BDs**	**Cluster BDs**
38452	10175	5471
Up-time	**Mean BDR**	**Mean Cluster BDR**
59.9 %	3.64E-5	1.96E-5

TD226CC in XBox-1



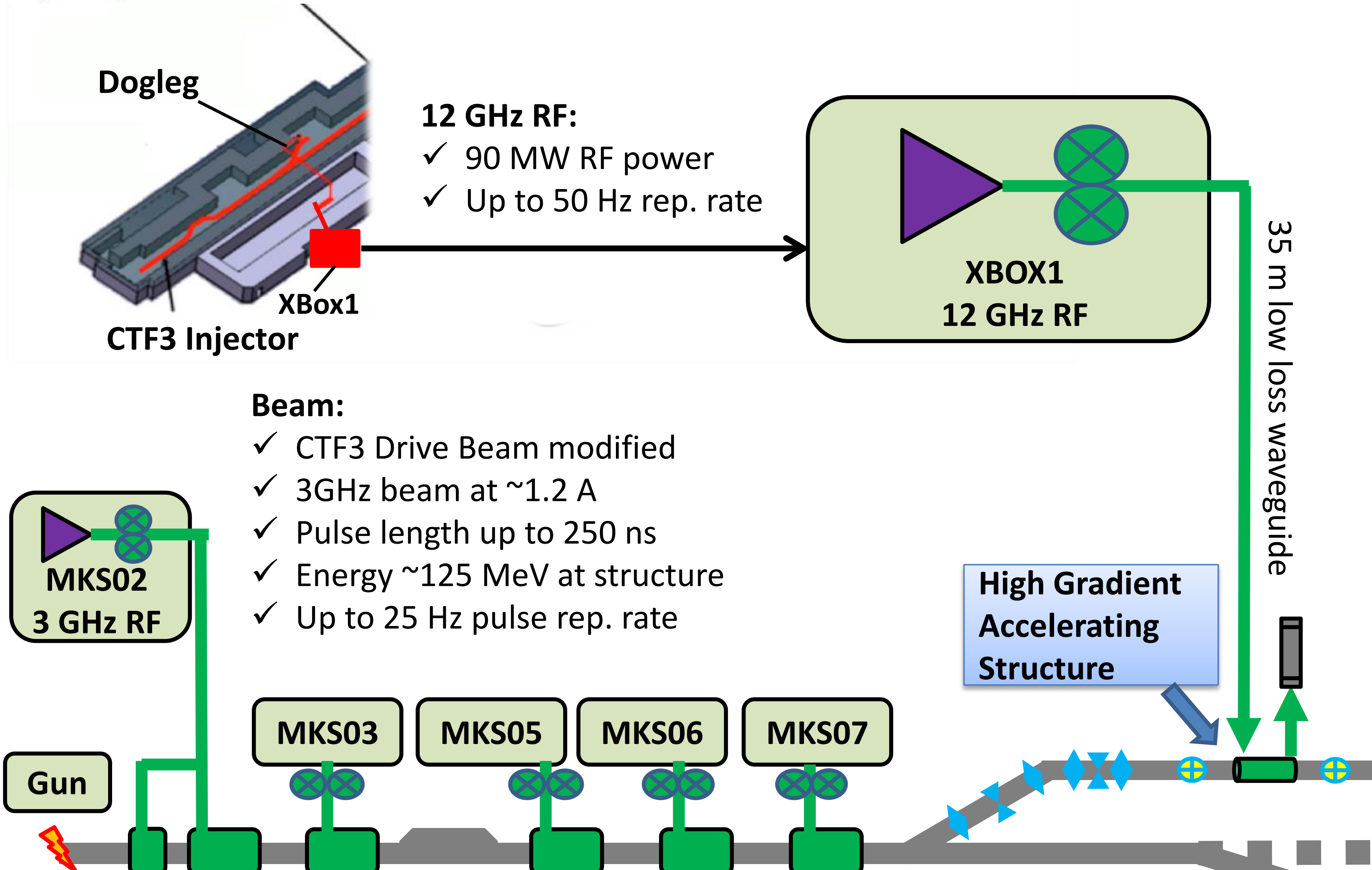
Dogleg Experiment

12 GHz RF:

- ✓ 90 MW RF power
- ✓ Up to 50 Hz rep. rate

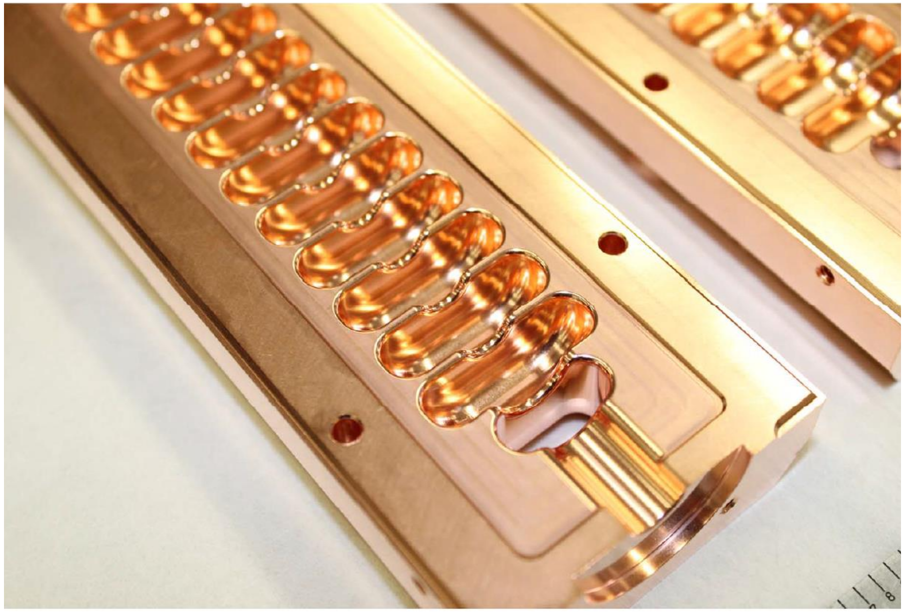
Beam:

- ✓ CTF3 Drive Beam modified
- ✓ 3GHz beam at ~1.2 A
- ✓ Pulse length up to 250 ns
- ✓ Energy ~125 MeV at structure
- ✓ Up to 25 Hz pulse rep. rate



Luis Navarro

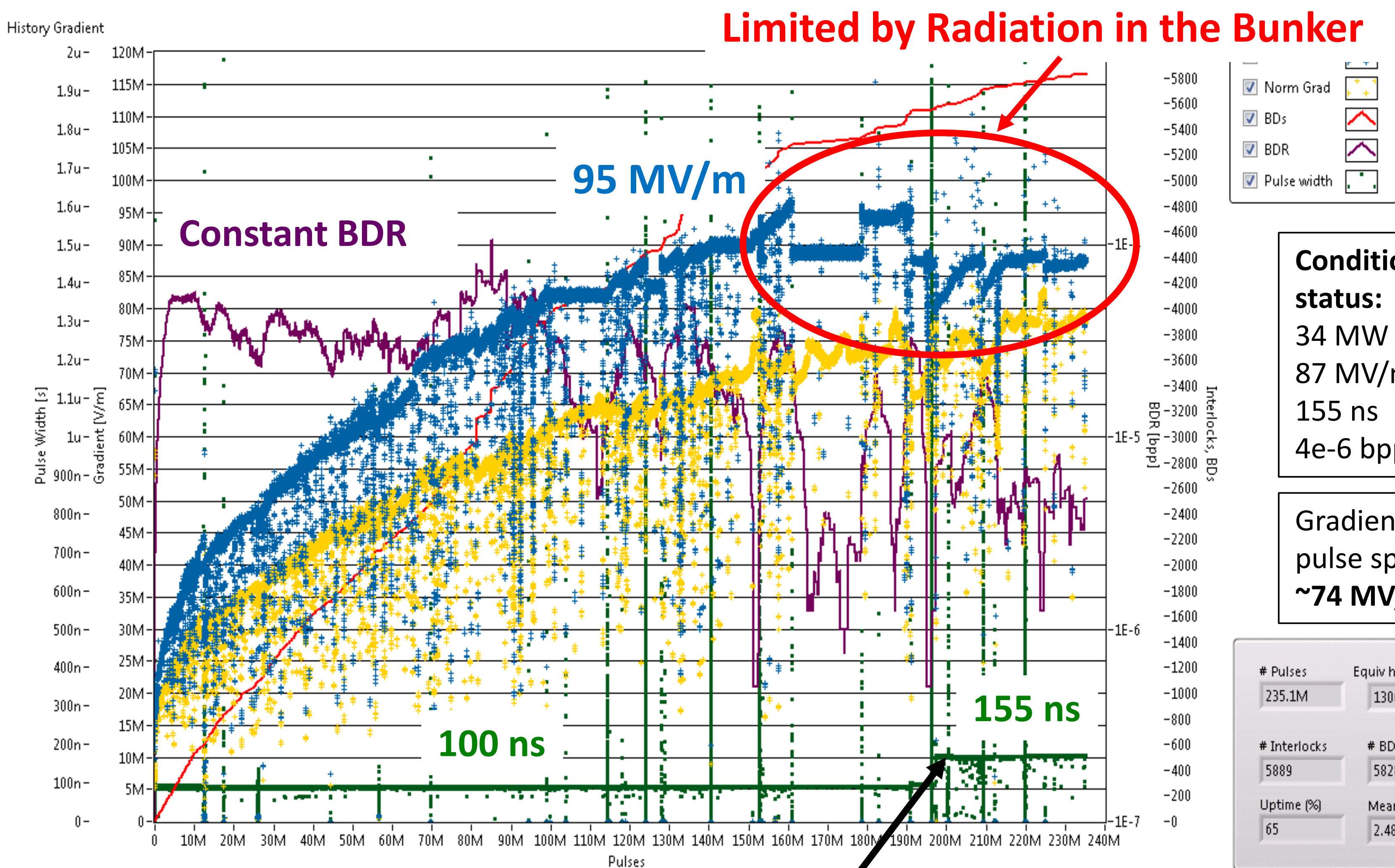
New direction – milled structures



vs.

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!

Xbox2: T24_open – full history



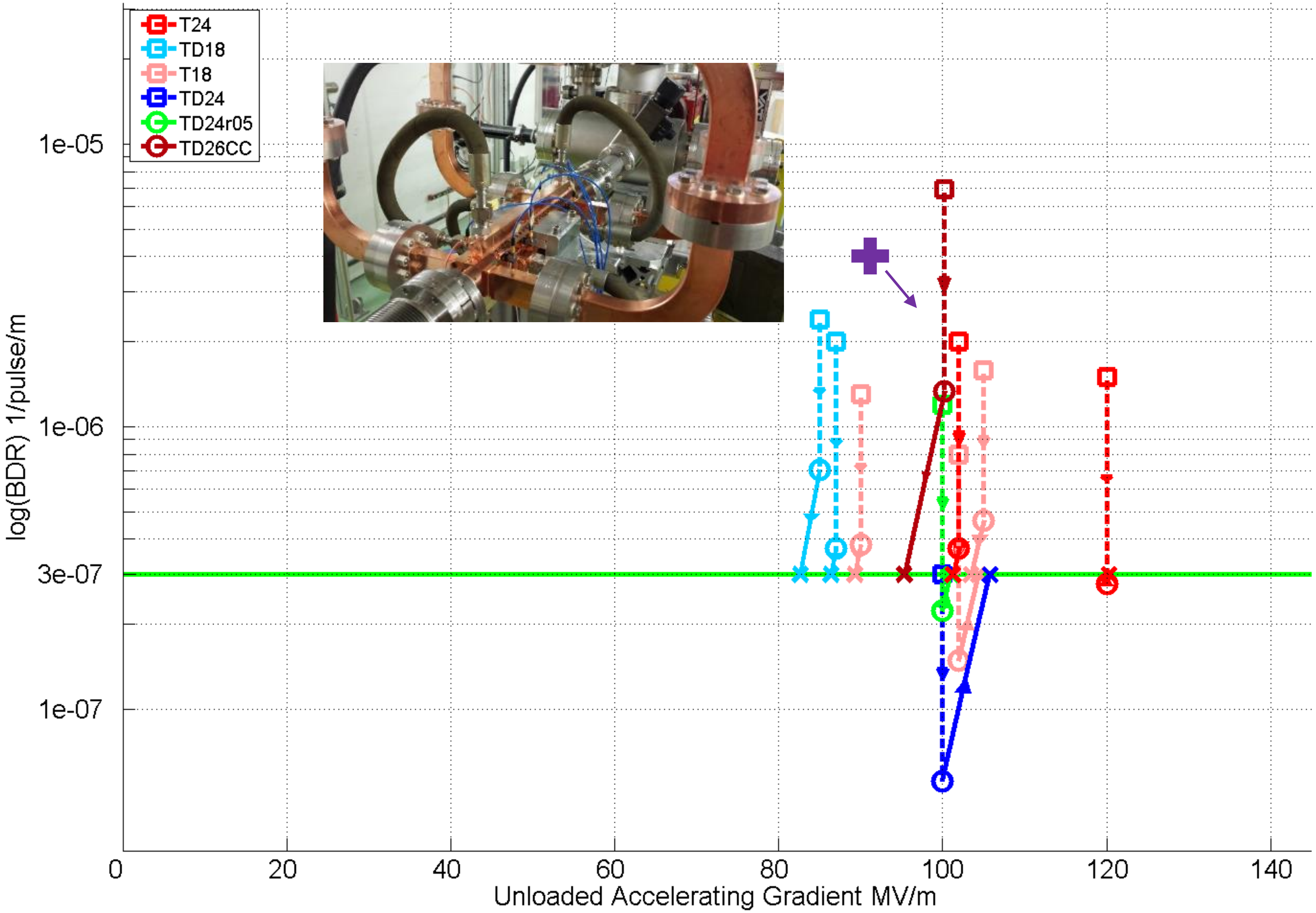
Changed pulse length to 155ns

Conditioning status:
34 MW
87 MV/m
155 ns
4e-6 bpp

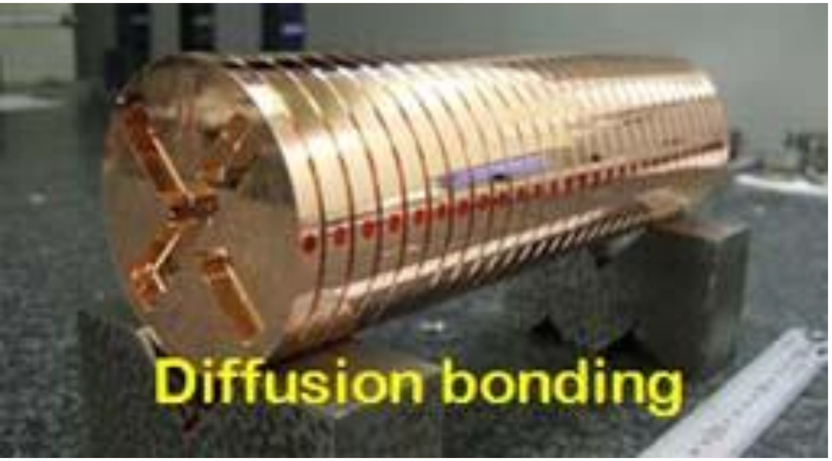
Gradient at CLIC pulse specs:
~74 MV/m

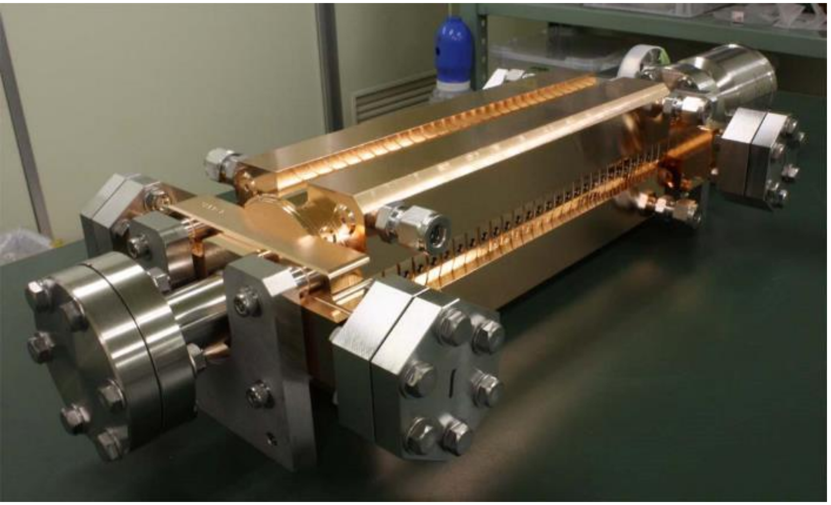
# Pulses	Equiv hours @50Hz	Run hours
235.1M	1306	2007.31
# Interlocks	# BDs	Cluster BDs
5889	5828	3577
Uptime (%)	Mean BDR	Mean Cluster BDR
65	2.48E-5	1.52E-5

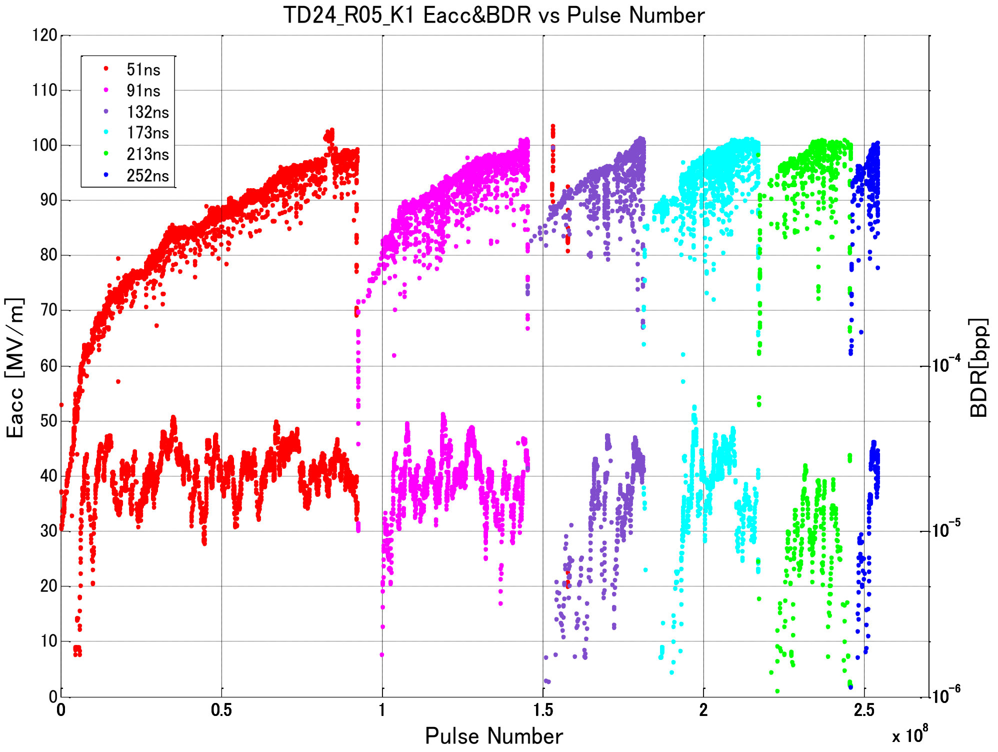
T24-Open in XBox-2



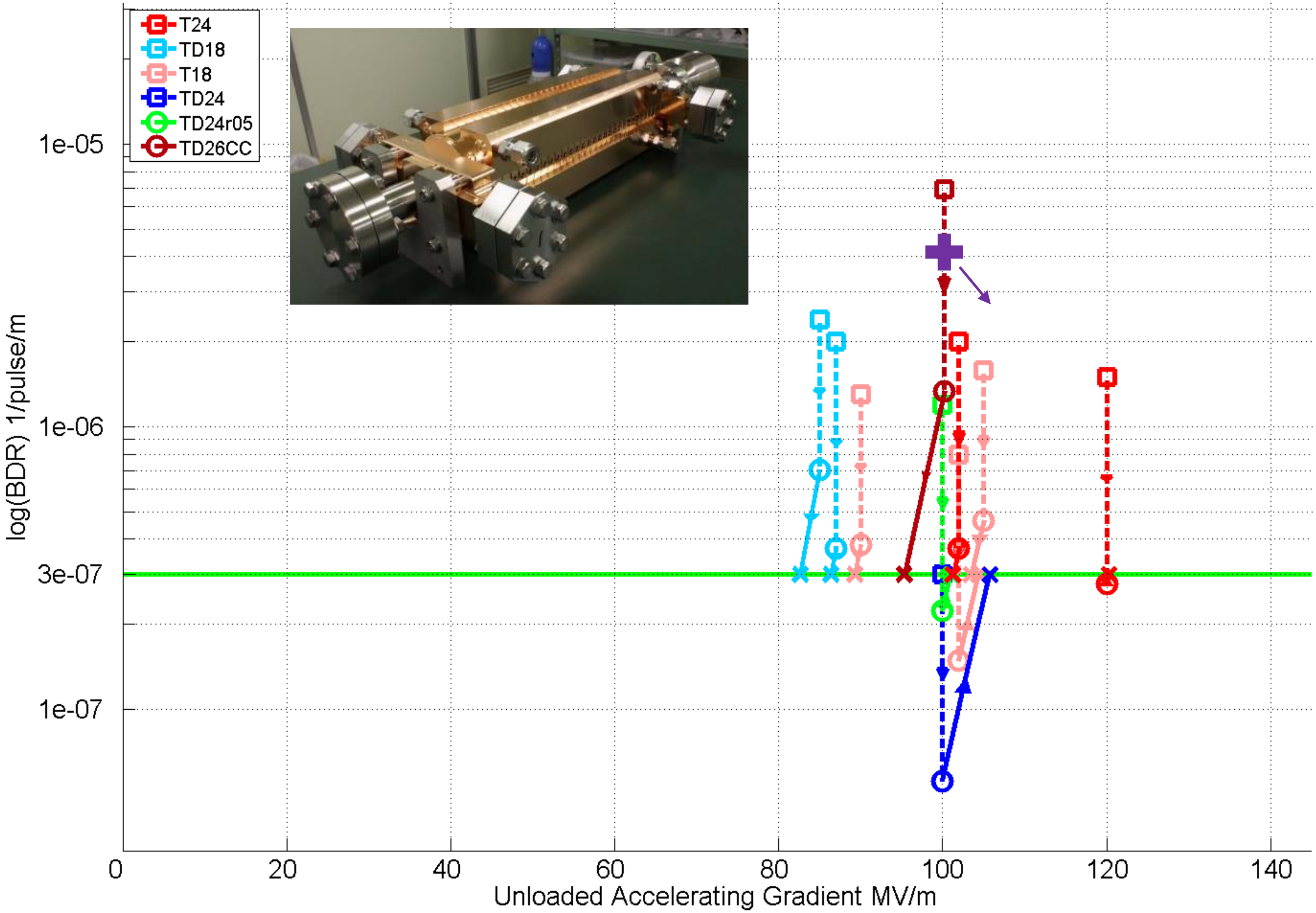
KEK TD24R05 in Nextef



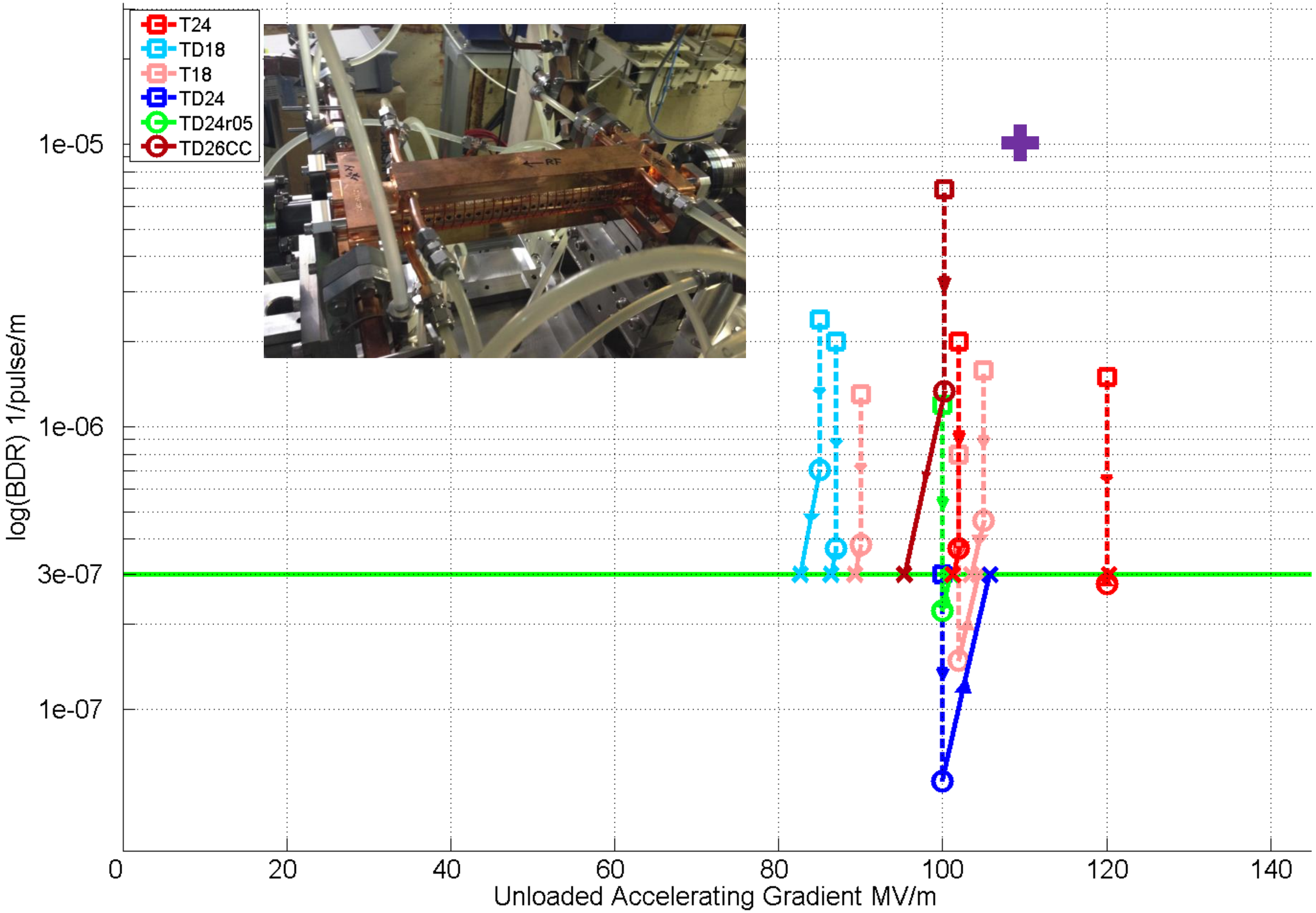




KEK TD24R05 in Nextef

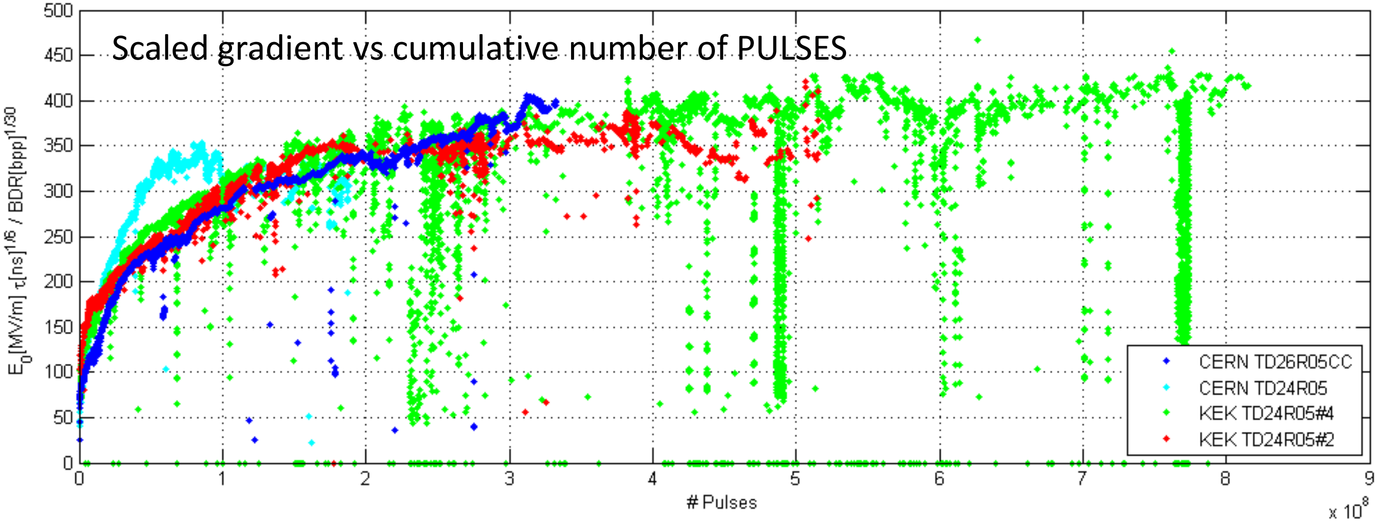


Tsinghua T24 in Nextef



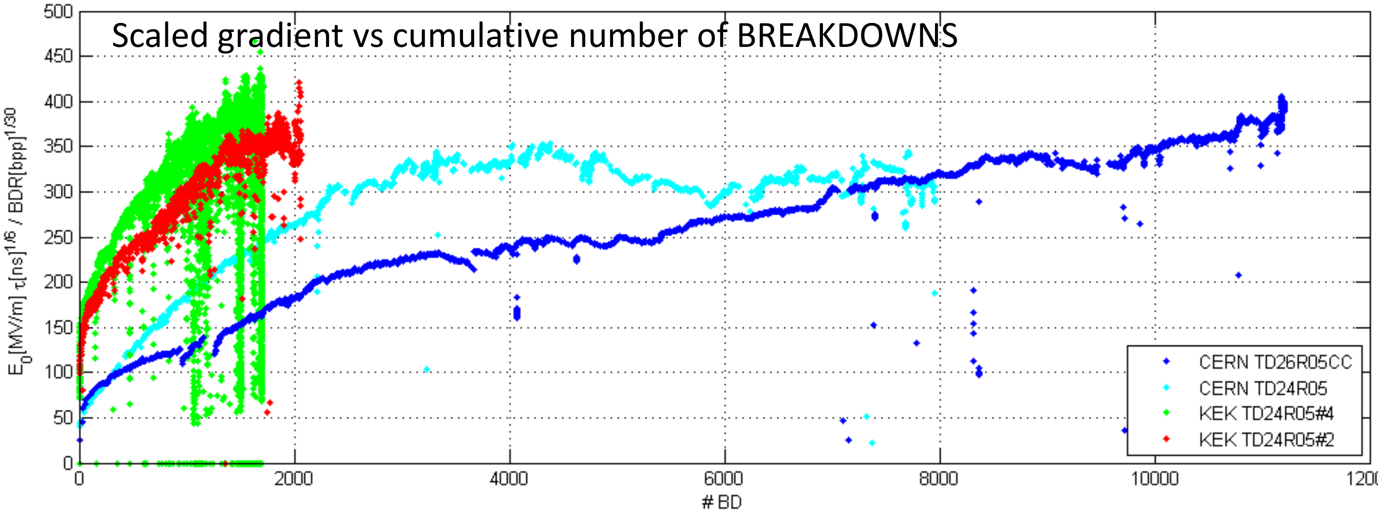
Understanding what’s going on

Comparing conditioning



Pulses

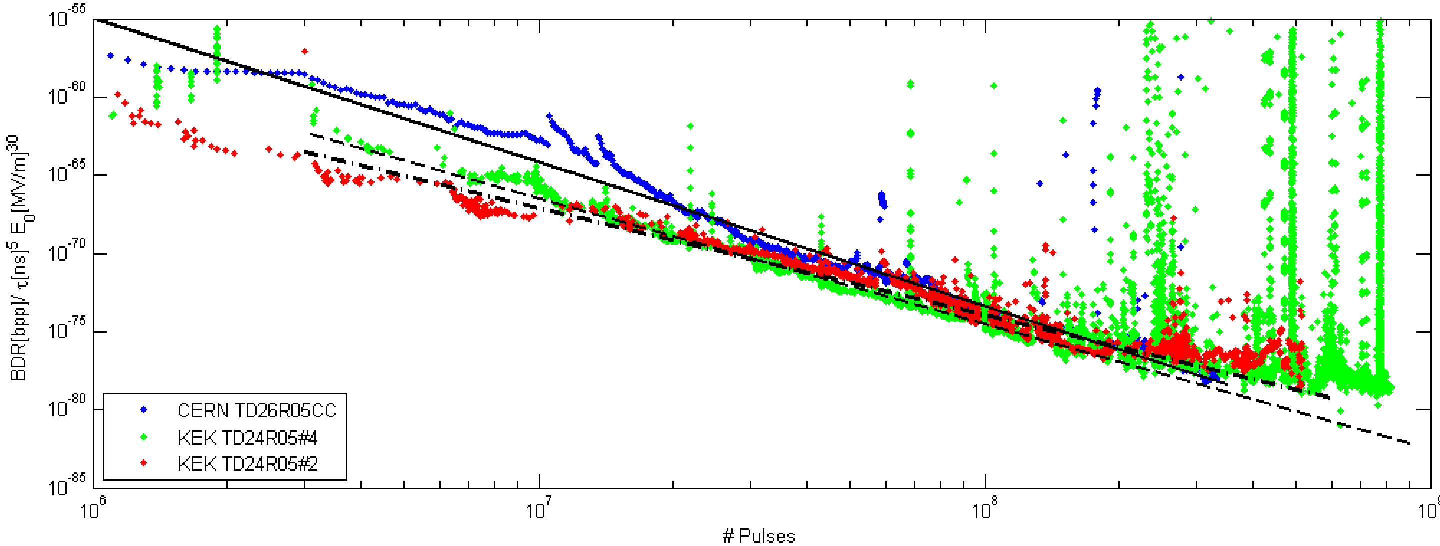
$$BDR \propto E^{30}\tau^{5}$$



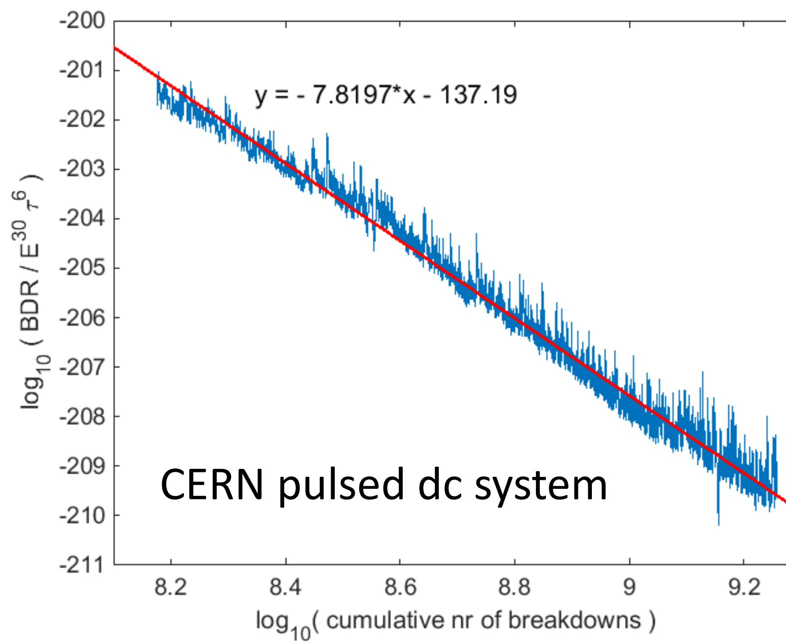
Breakdowns

Long term behaviour

Normalized BDR



What happens when you run for a long time?
Gradient stops increasing but BDR goes down and down – but must stay below critical level.

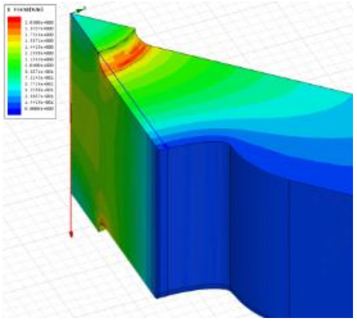


RF design for high gradient

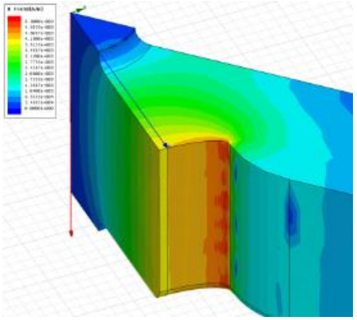
We have well developed rf design criteria which **predict the gradient** of pulsed high-gradient structures. The criteria cover the physical phenomena which limit accelerating gradient:

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

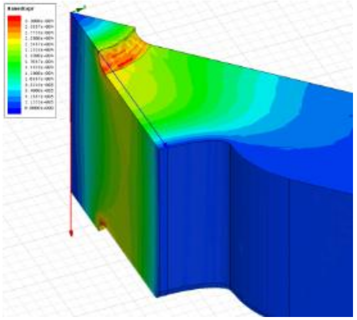
E_s/E_a

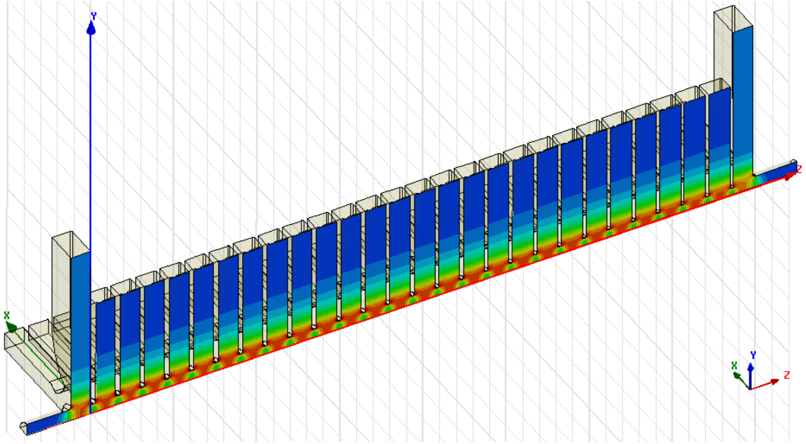


H_s/E_a



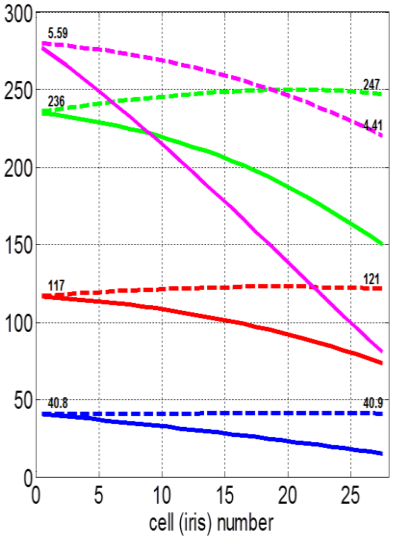
S_c/E_a^2





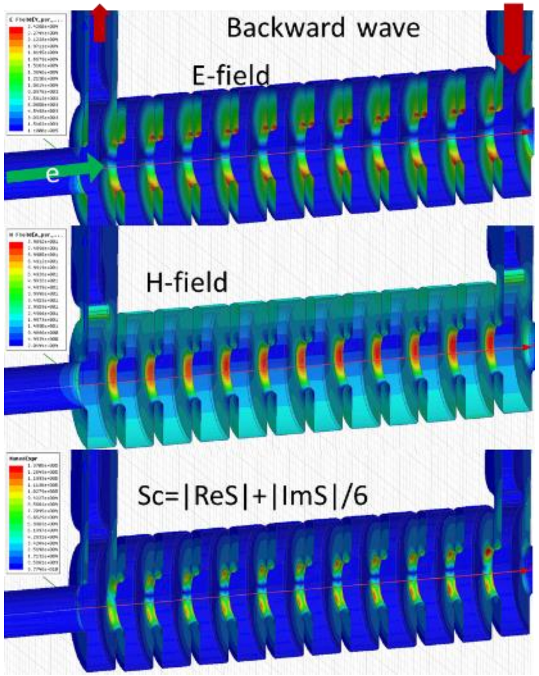
New CLIC 3 TeV baseline

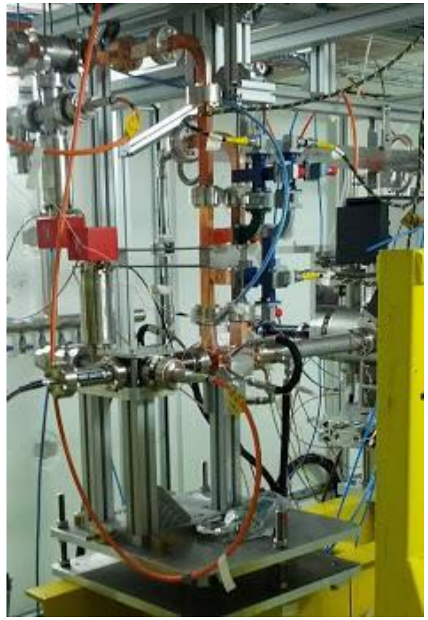
H. Zha, A Grudiev



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

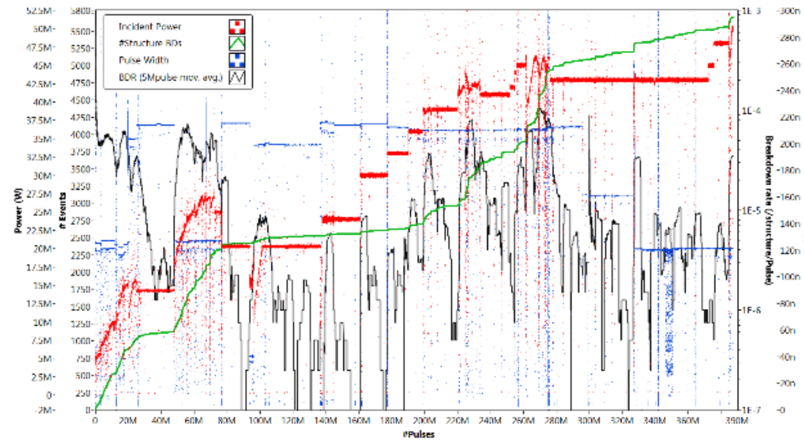
CLIC crab (deflecting) cavity





G. Burt

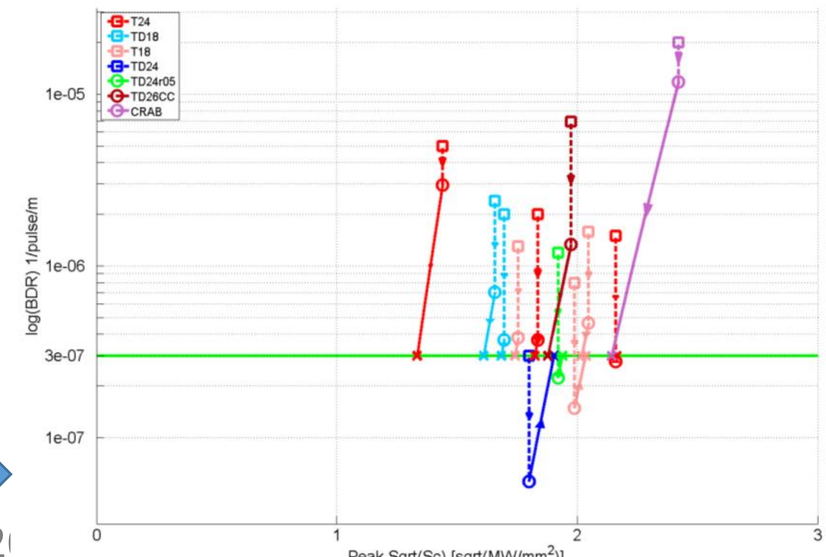
Lancaster crab cavity: rf design and installed in XBox-2.



B. Woolley

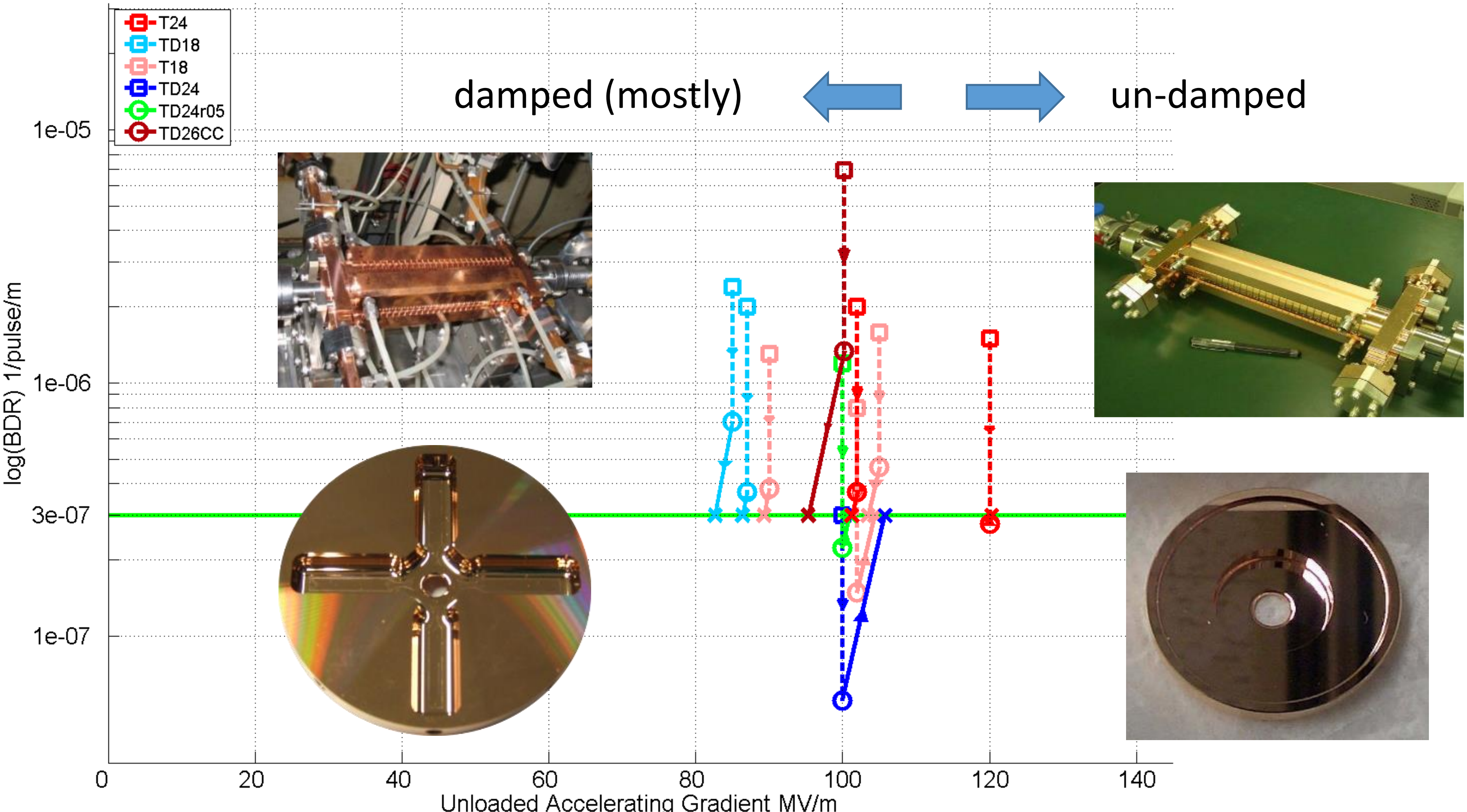
Up to 47 MW!

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



A. Degiovanni

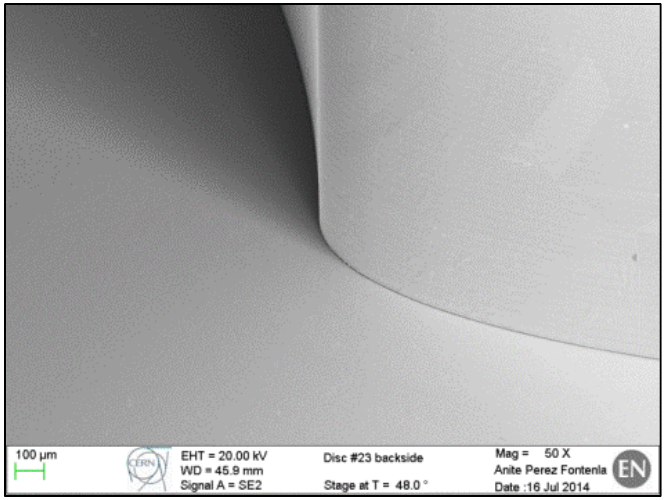
Gradient Summary

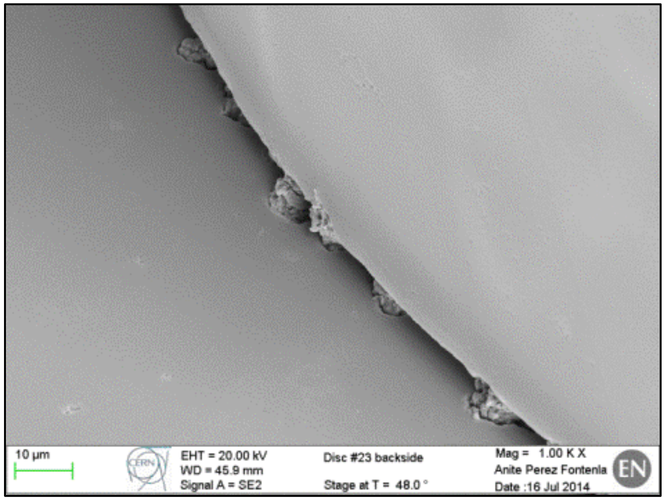


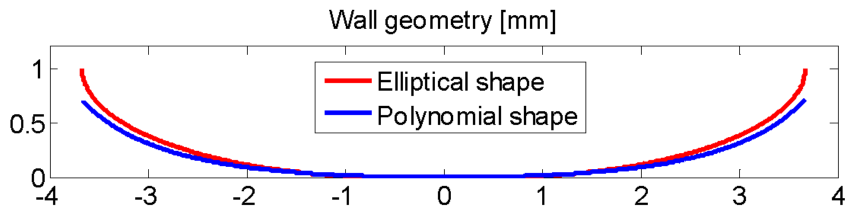
A. Degiovanni

Directions for improvement

- 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.





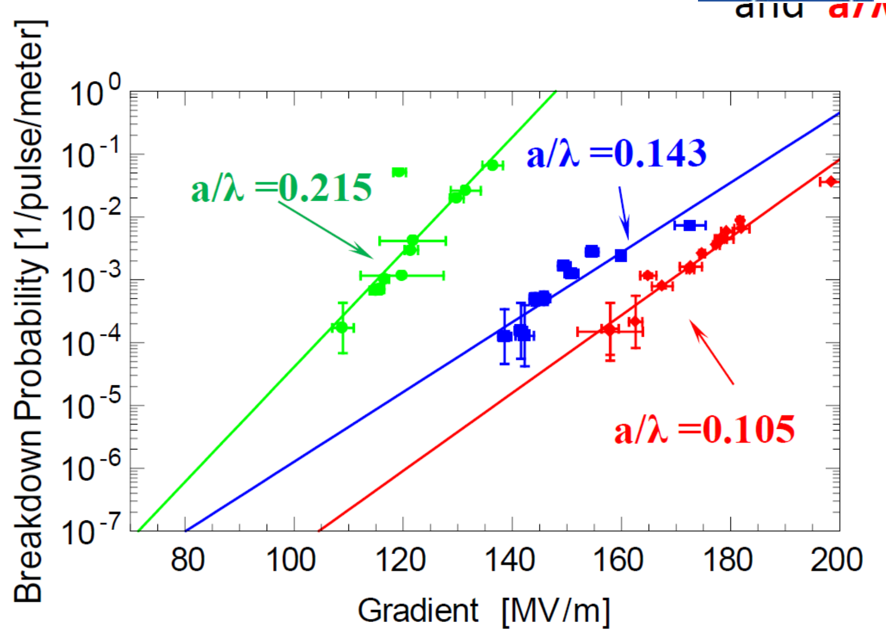


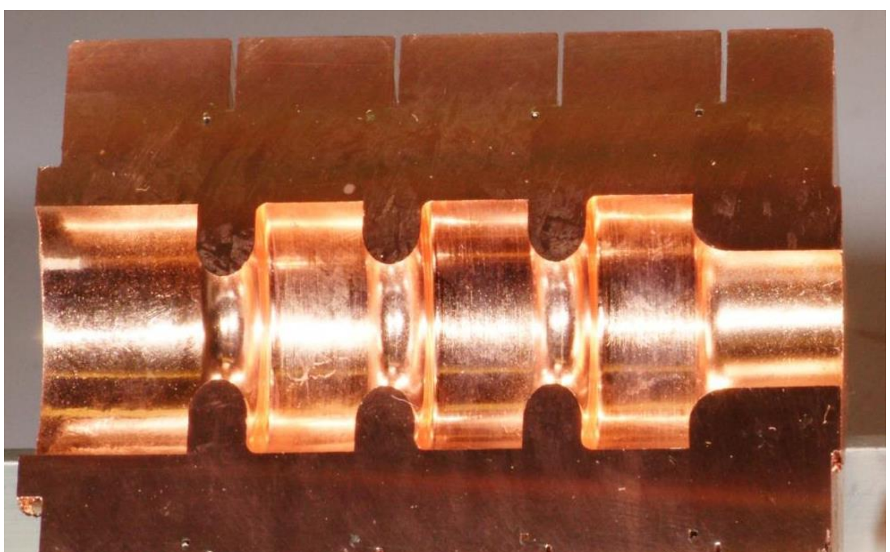
Single cells

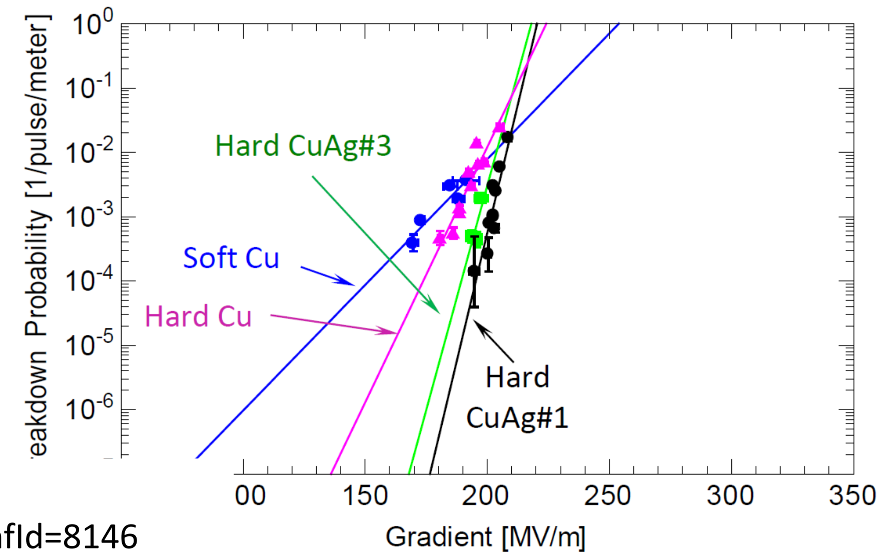
There’s a hidden story behind the full structures which emerges when looking at single cells.

SLAC has a long-standing single cell testing program.

Gradients up to 200 MV/m are possible.



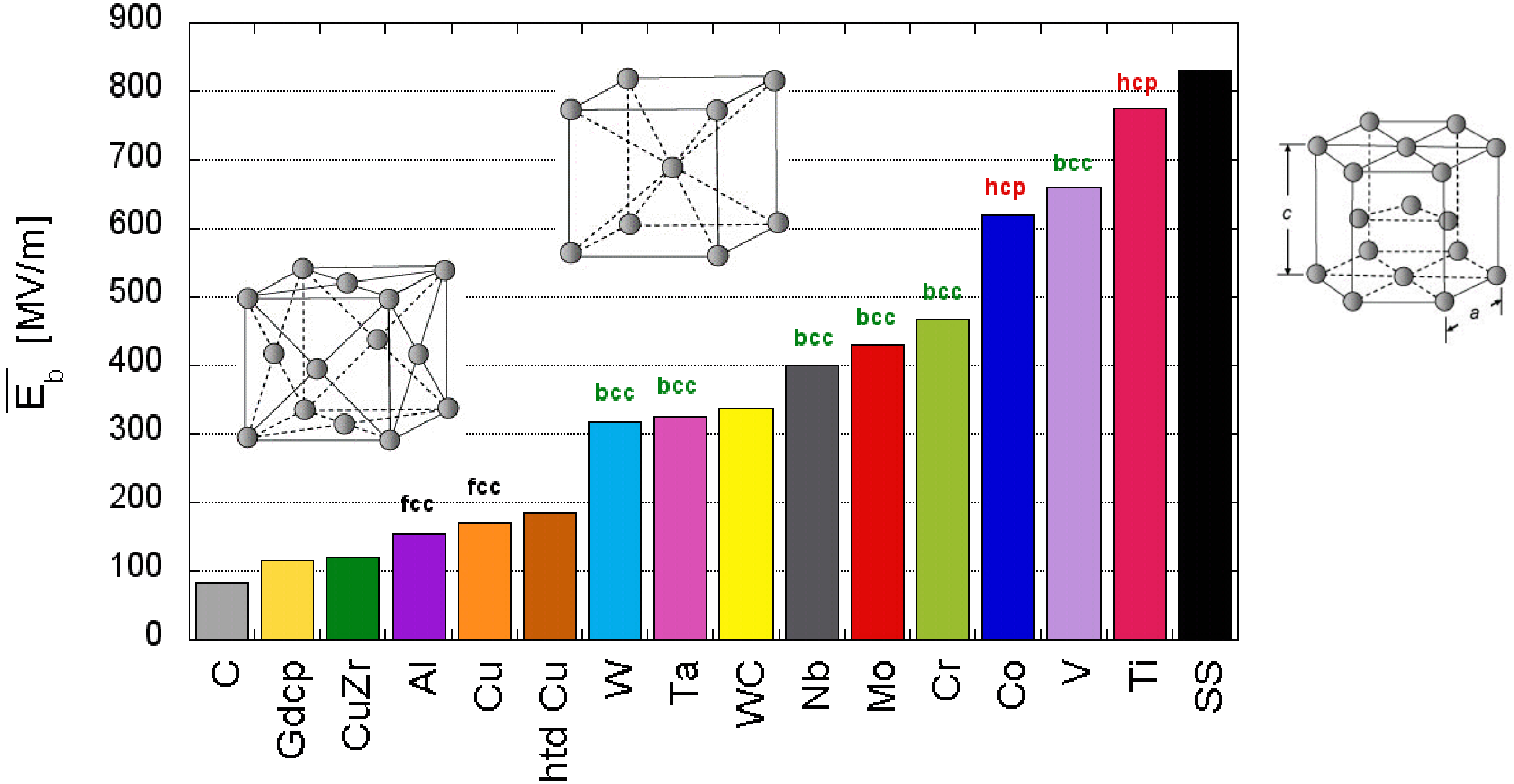




V. Dolgashev, EAAC2015

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

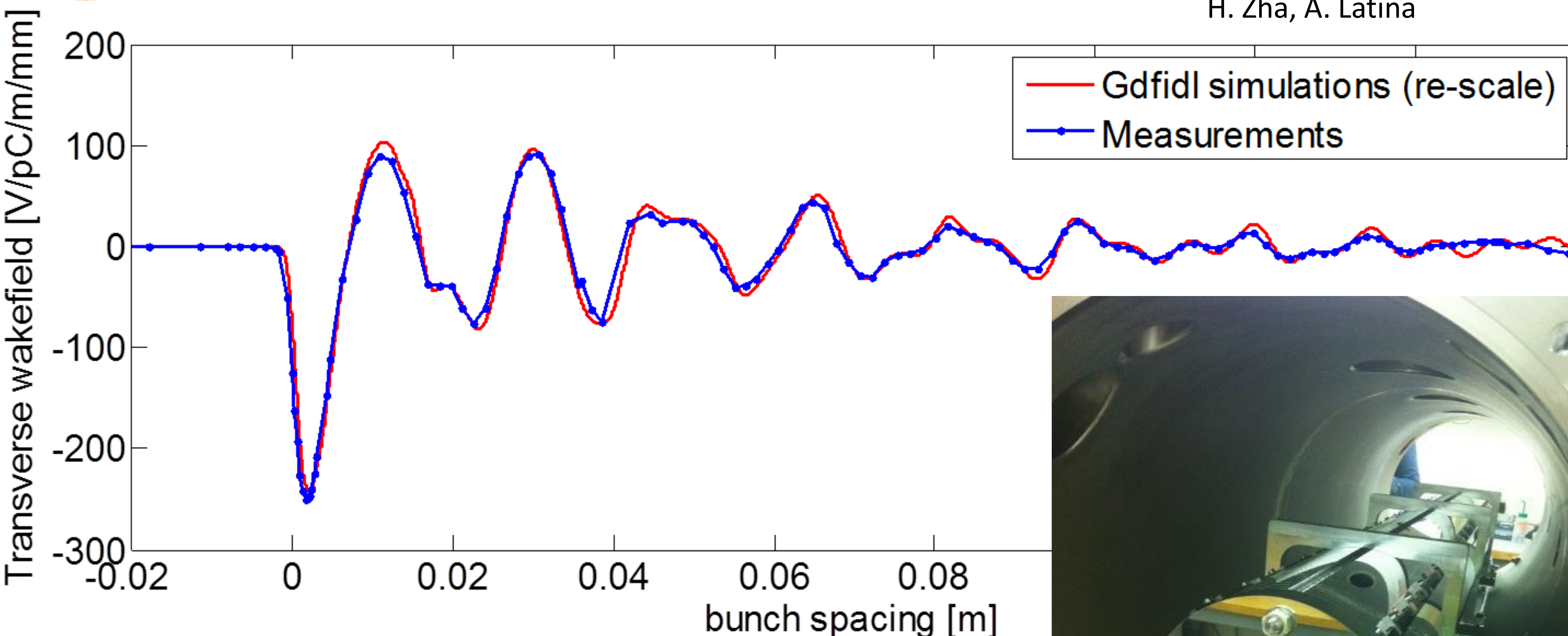
Material dependence in pulsed dc

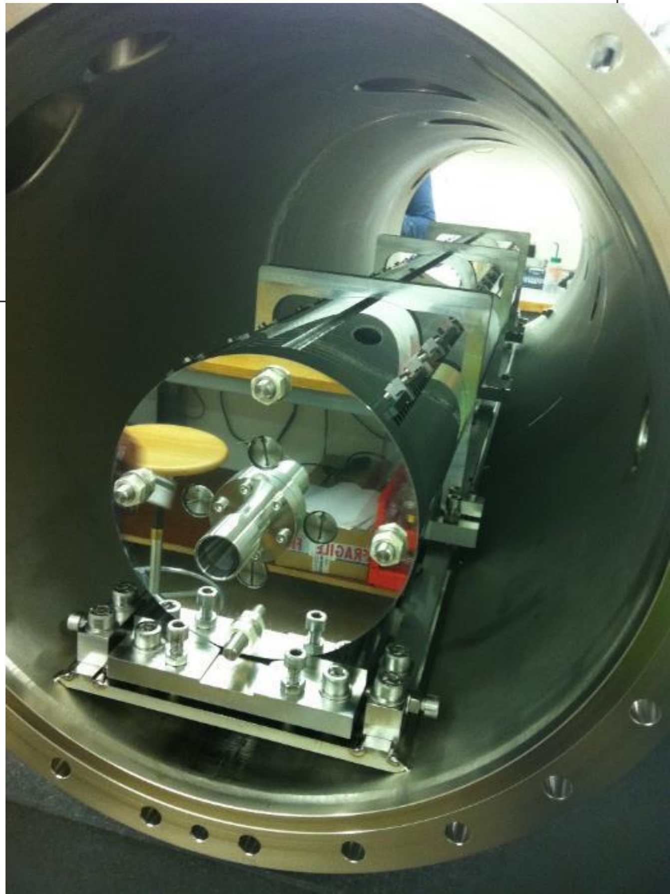


A. Descoeudres, F. Djurabekova, and K. Nordlund,
DC Breakdown experiments with cobalt electrodes,
CLIC-Note 875, 2011

Wakefield suppression

H. Zha, A. Latina





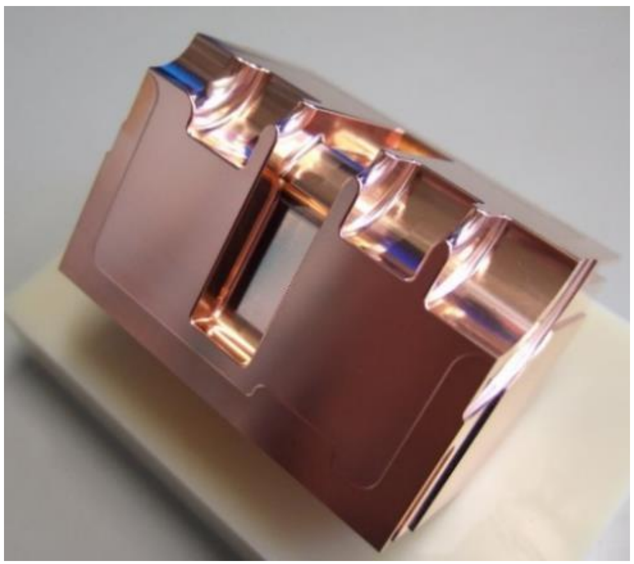
Wakefield from 1.5 m long, 6 structure length, prototype measured directly with beam at the FACET facility at SLAC.

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

More wakefield suppression

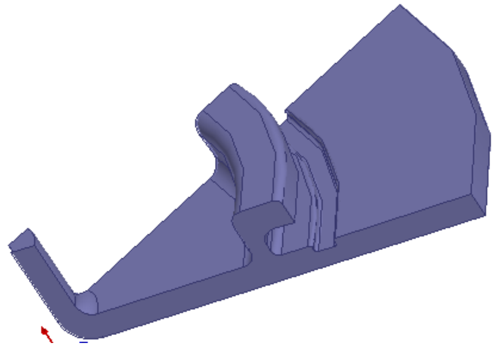
Ongoing development of alternatives for HOM damping.

T. Abe, T Higo

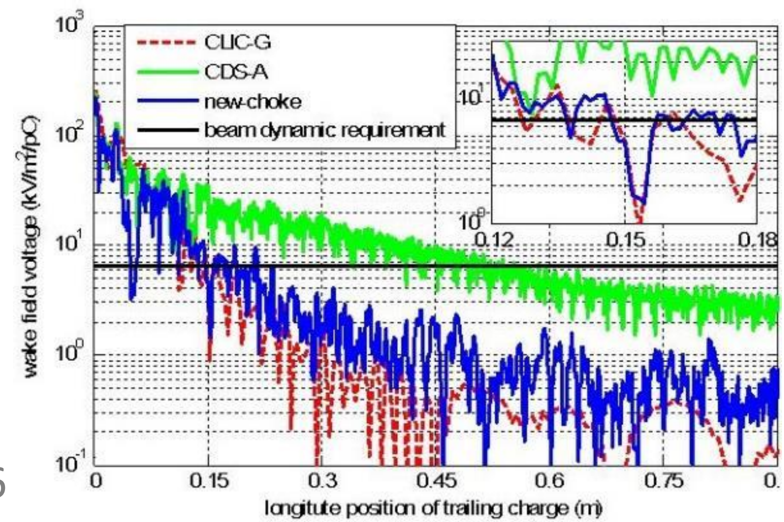


Quadrant structure development at KEK

J. Shi, H Zha



Choke-mode cavity, Tsinghua U. development



Applications

High-gradient and X-band Applications

We all hope that the LHC soon uncovers the new physics which really opens the next chapter of particle physics, perhaps with a TeV-range linear collider playing a key role.

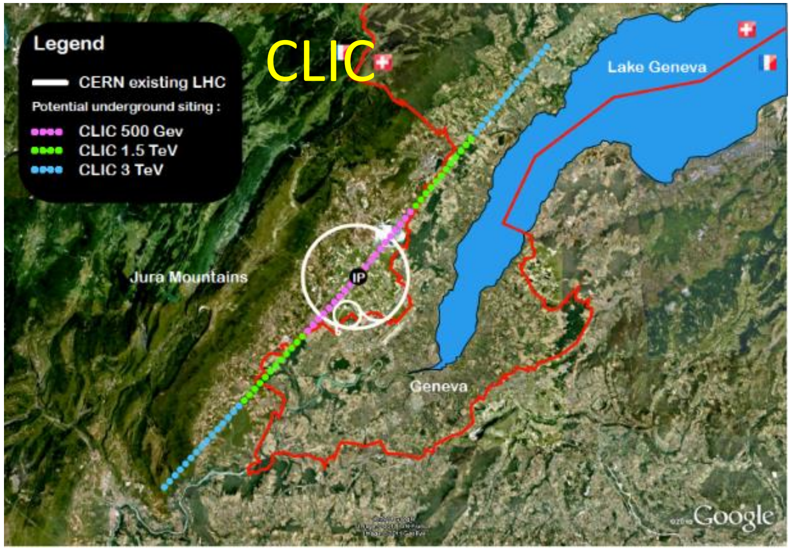
But it will take time to get such a project approved.

In the mean time there is still a lot we can do to make such a machine as high performance and as cheap as possible.

One of the most efficient ways to do this is to work with other projects which benefit from high-gradient and X-band rf technology.

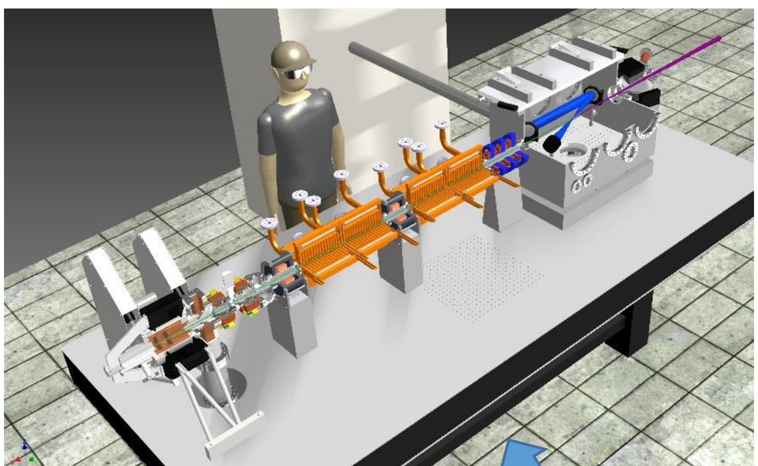
We get new ideas, a chance to test existing ideas, improve the commercial base, improve (maintain!) the intellectual base etc.

Scale of applications



Linear collider - TeV

XFEL – 1 to 10 GeV



Thompson/Compton source – few 100s MeV

Compact Compton source few 10s MeV

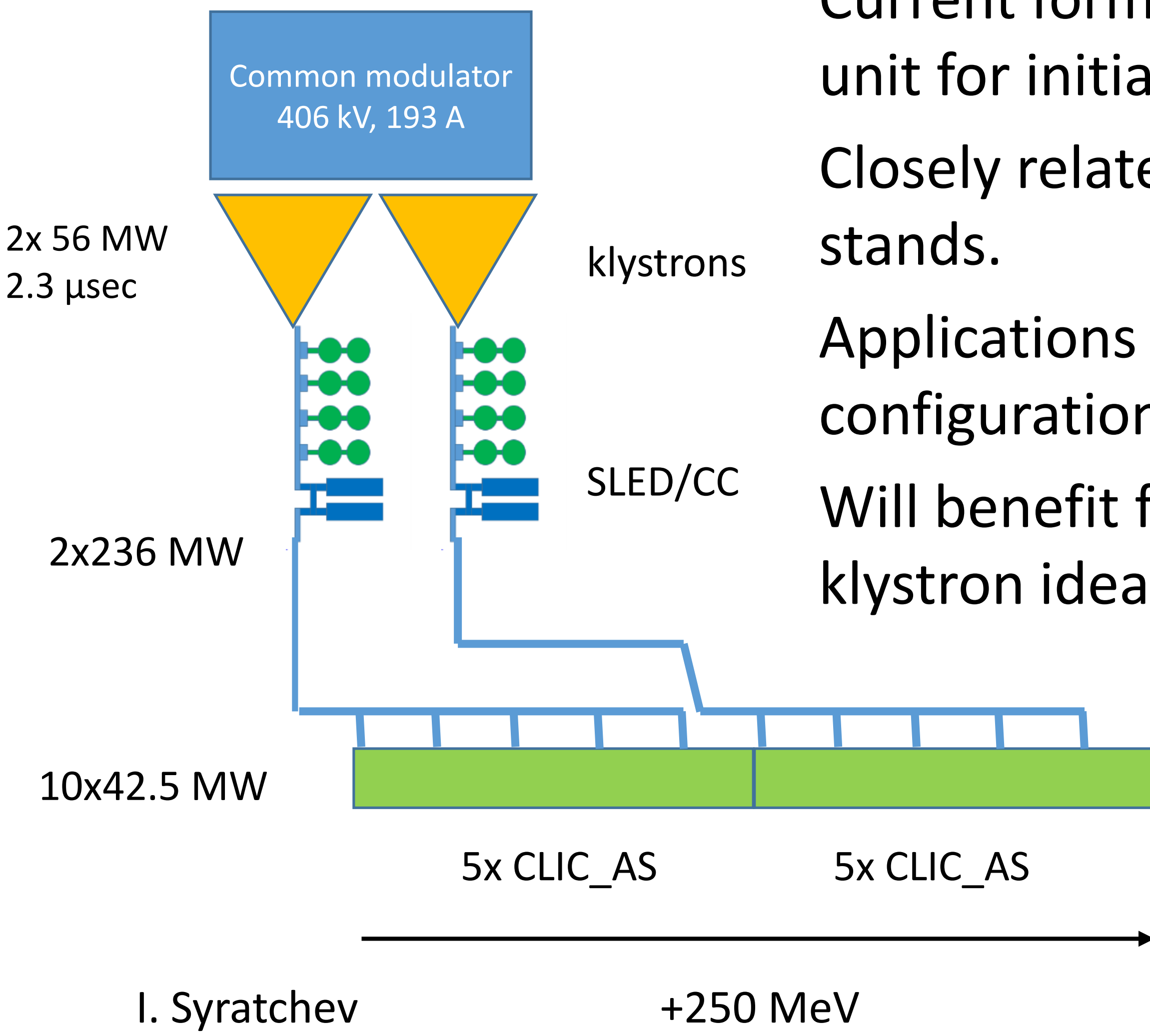
Linac rf system

Current form of klystron-based linac rf unit for initial energy stage of CLIC.

Closely related to operating test stands.

Applications use variants of this configuration.

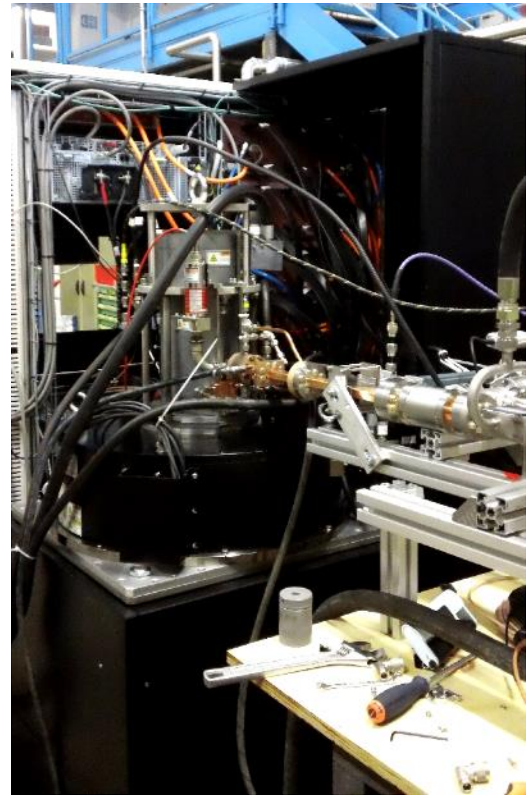
Will benefit from new high-efficiency klystron ideas.



I. Syratchev

Commercial X-band rf power sources

CPI 50 MW, 1.5 μs, 50 Hz



Toshiba 6 MW, 5 μs, 400 Hz

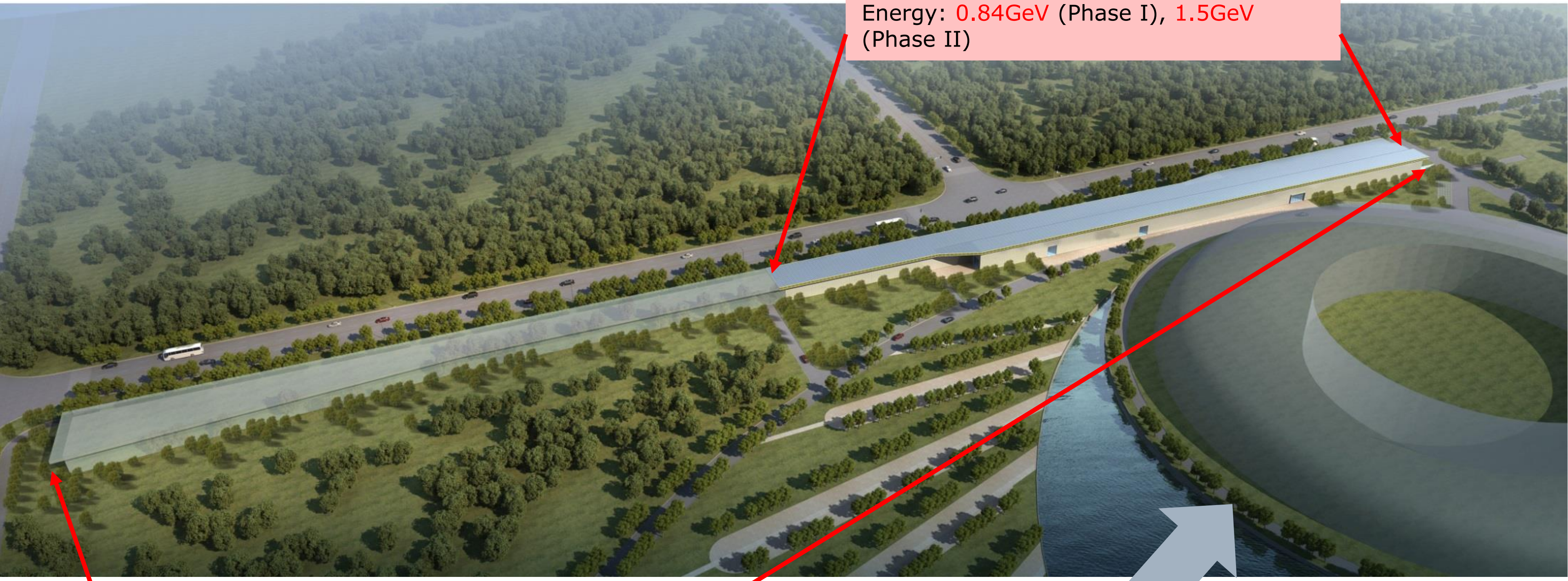
Commercial X-band klystrons at CERN. Availability of **commercial** rf power sources essential for spread and development of technology.

Shanghai Photon Science Center at SINAP

SXFEL: Shanghai Soft X-ray FEL

S-band, C-band, X-band

Energy: 0.84GeV (Phase I), 1.5GeV (Phase II)



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

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

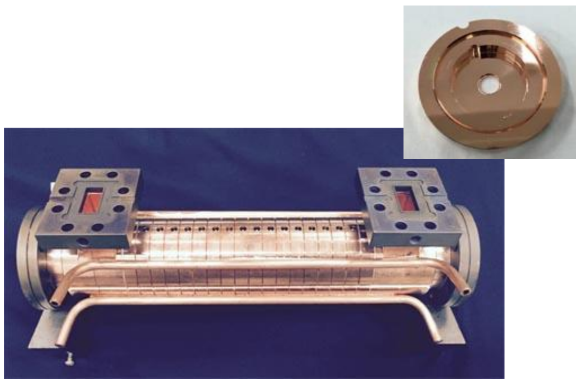
Total length: About 550 meters

SSRF: Shanghai Synchrotron Radiation Facility

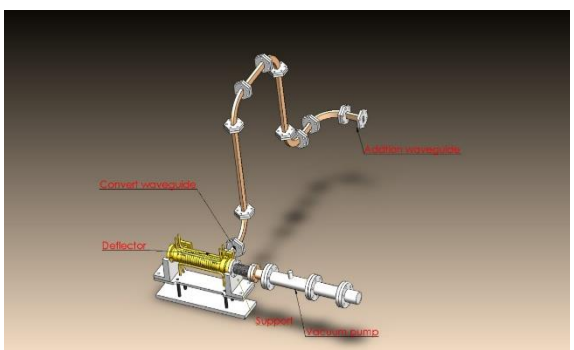
Energy: 3.5GeV, user operation

Current status of X-band technology

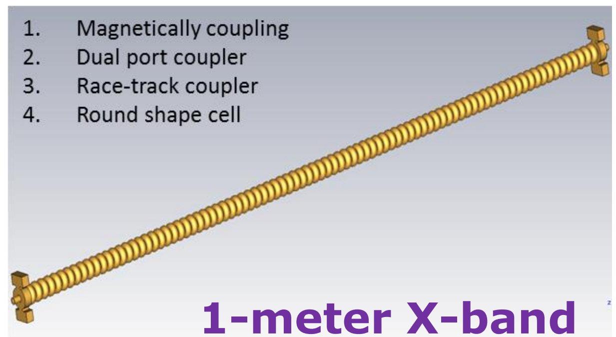
1. Prototype of X-band deflector is ready, and will be delivered to KEK soon for high power test this year.
2. 1-meter X-band accelerating structure for SXFEL has been designed, and start fabrication soon this year.



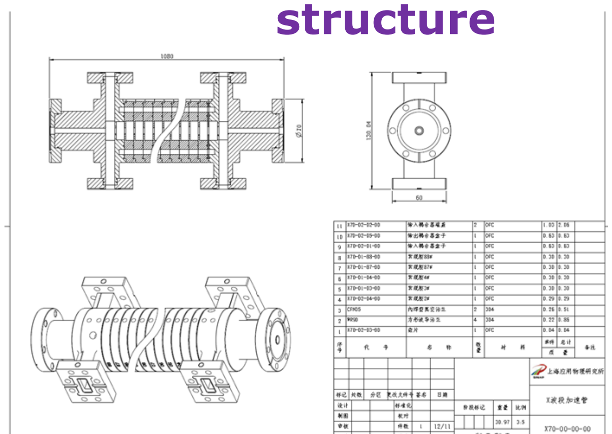
X-band Deflector



High power test at KEK

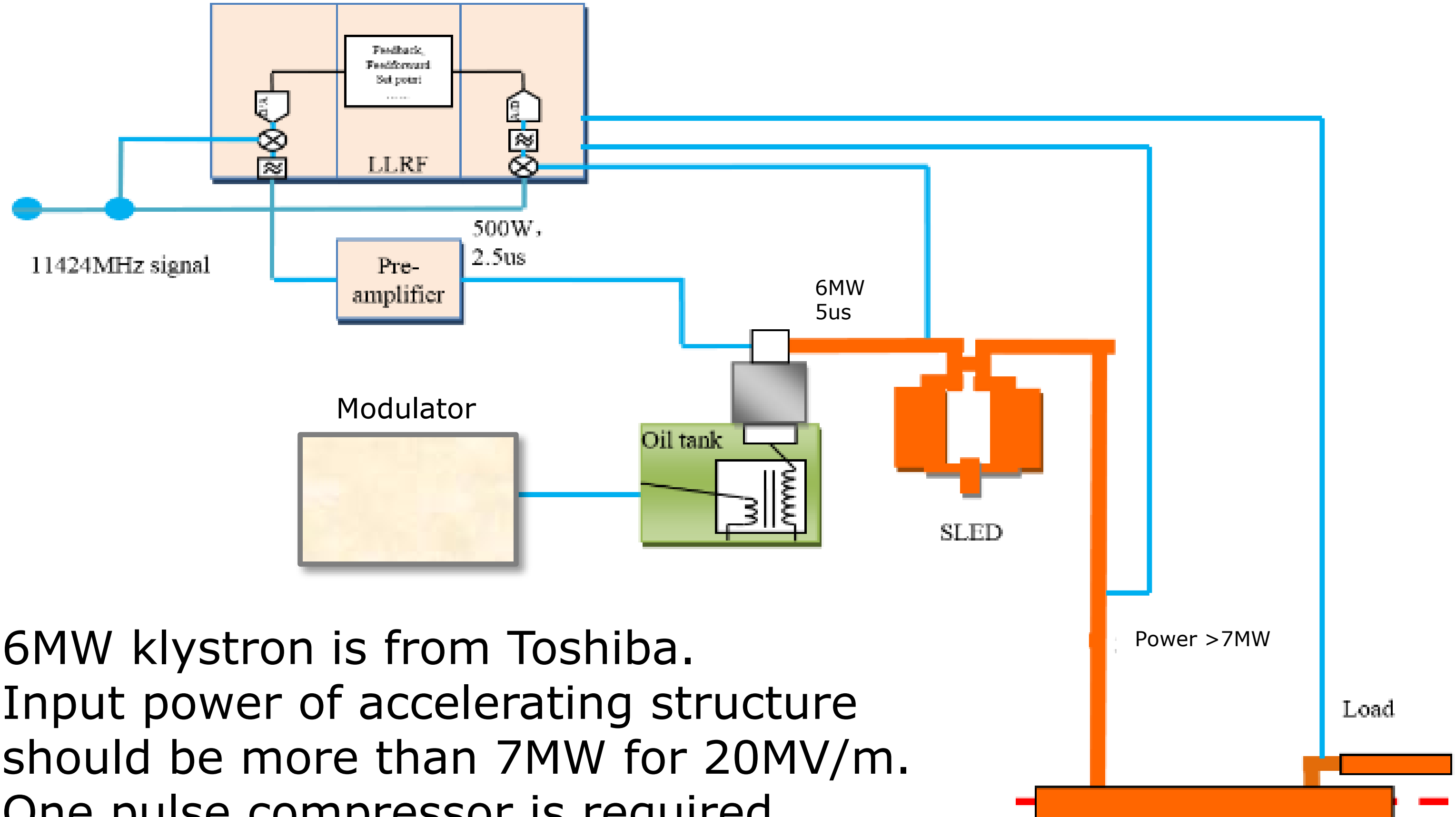


1-meter X-band structure



Frequency	11424MHz
Phase advance	4π/5
Cell No.	89+2
Effective length	944.73mm
Cell length, d	10.497mm
Iris thickness, 2a	1.5 mm
Diameter, 2b	23.379~22.556 mm
Ratio of elliptic radius, b_a	1.8
Aperture, a_r	4.3~3.05.mm
Group velocity, Vg/c	3.45%~1.12%
Shunt impedance, R	93.93~125.62MΩ/m
Attenuation factor, τ	0.61
Filling time, t_f	150 ns
Sc	4.14~2.33 MW/mm^2
Emax/E0	2.68~2.02
Hmax/E0	2.68~2.39 mA/V
Input power, P_{in}	52MW @65MV/m 80MW @80MV/m
Two-Klystrons units	34 @65MV/m 51 @80MV/m

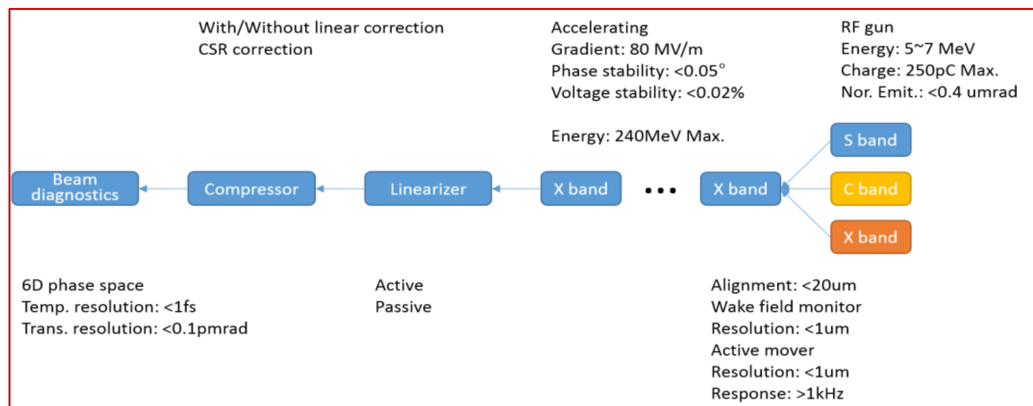
X-band RF unit for SXFEL



1. 6MW klystron is from Toshiba.
2. Input power of accelerating structure should be more than 7MW for 20MV/m.
3. One pulse compressor is required.
4. LLRF is based on MTCA, Phase stability should be better than 0.36 degree, and amplitude should be better than 0.04%.

X-band experiment setup plan in the future

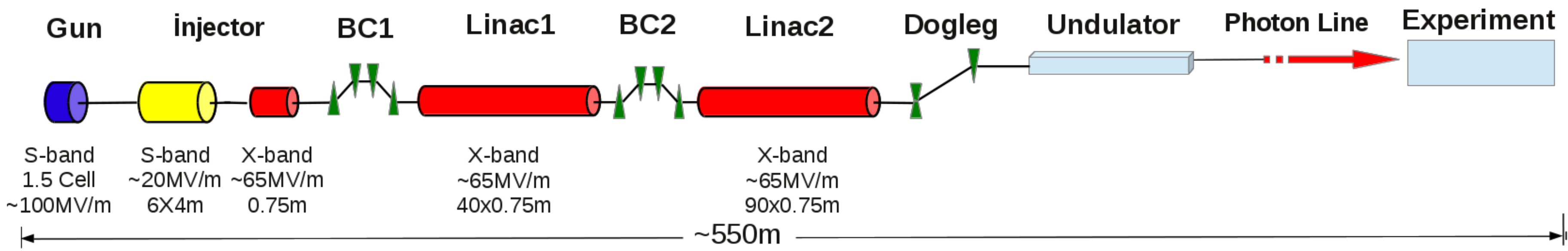
1. First step, one 50 MW X-band high power test platform will be set up based on short-term plan.
2. In the future, SDUV-FEL facility will be removed in two years, and 50m tunnel is dedicated for X-band technology R&D, specially for FEL linac development based on X-band.
3. One dedicated fabrication workshop almost is constructed, and now is waiting for Hydrogen furnace, which will be ready on April this year.



X-band Accelerator Test Facility plan at SINAP

Proposed Layout-1

S-Band based injector + X-Band based main accelerator

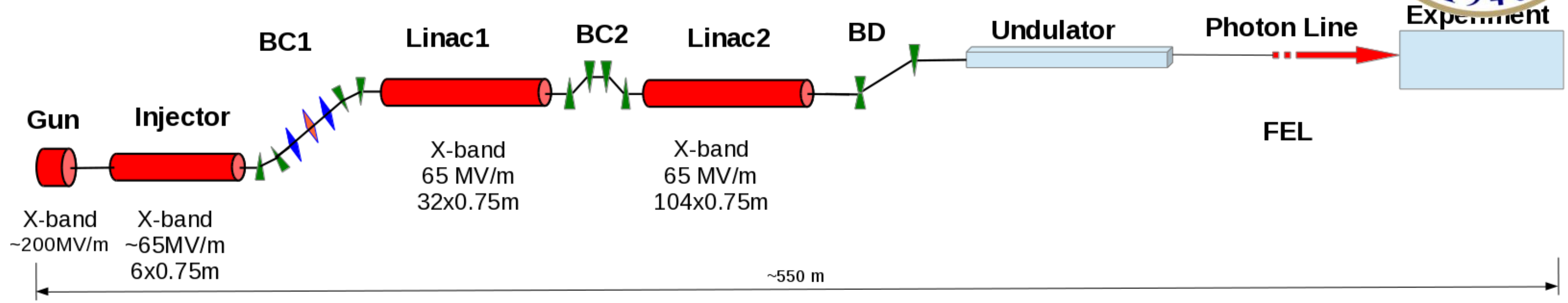


- It consist of

- RF photocathode gun → S band structure delivering beam @7 MeV with 250 pC charge, 9ps (800μm) lengt and 0.25 mm rad emittance
- Injector → consist of S-band structures and one X-band structure as linearizer, accelerating beam up to 300 MeV
- Two main linacs → consist of X-band modules, accelerating beam in two stage 0.3 GeV → 2 GeV and 2 GeV → 6 GeV
- Two bunch compressors , Beam delivery lines , Undulator(s), Laser transport line (s)

Proposed Layout-2

All X-Band based injector and main accelerator



- It consist of

■ RF photocathode gun → X band structure delivering beam @7 MeV with 250 pC charge, 2.5 ps (200μm) lengt and 0.45 mm rad emittance

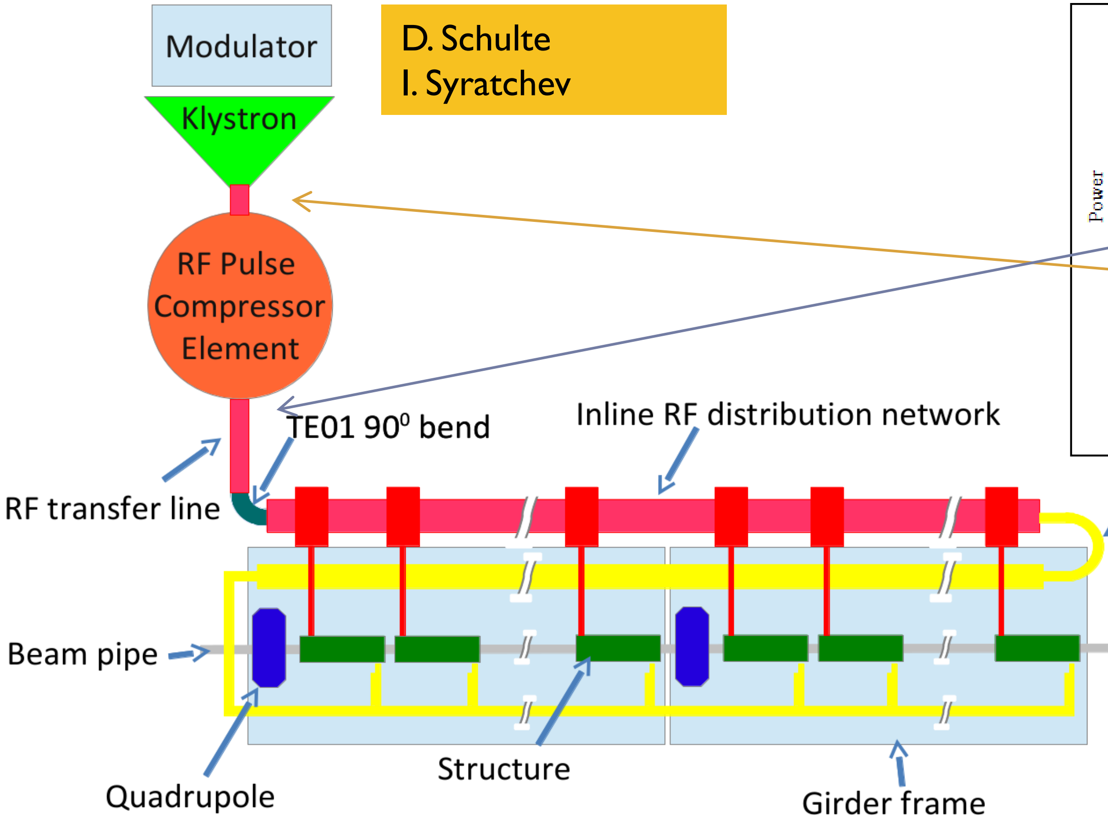
■ Injector → consist of X-band structures and one X-band structure to optimize chirp, accelerating beam up to 200 MeV

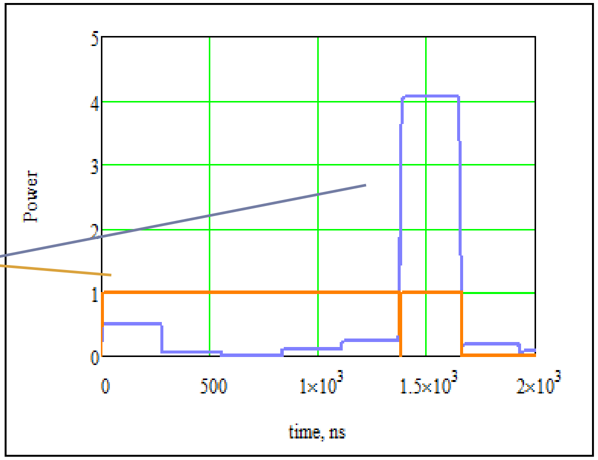
■ Two main linacs → consist of X-band modules, accelerating beam in two stage 0.2 GeV → 1.5 GeV and 1.5 GeV → 6 GeV

■ Two bunch compressors , Beam delivery lines , Undulator(s), Laser transport line (s)

Main Linac Module Layout

D. Schulte
I. Syratchev





Depending on compressor type we can adjust
- ➢N klystron
- ➢N structure

- In case of using SLED type of pulse compressor
  - ➢ 50 MW, 1.5 μs input power is compressed to 150 ns with 460 MW
- This unit should provide ~516 MeV acceleration beam loading.
- Need ~14 RF structures.

Australian Synchrotron

Turning bright ideas into brilliant outcomes

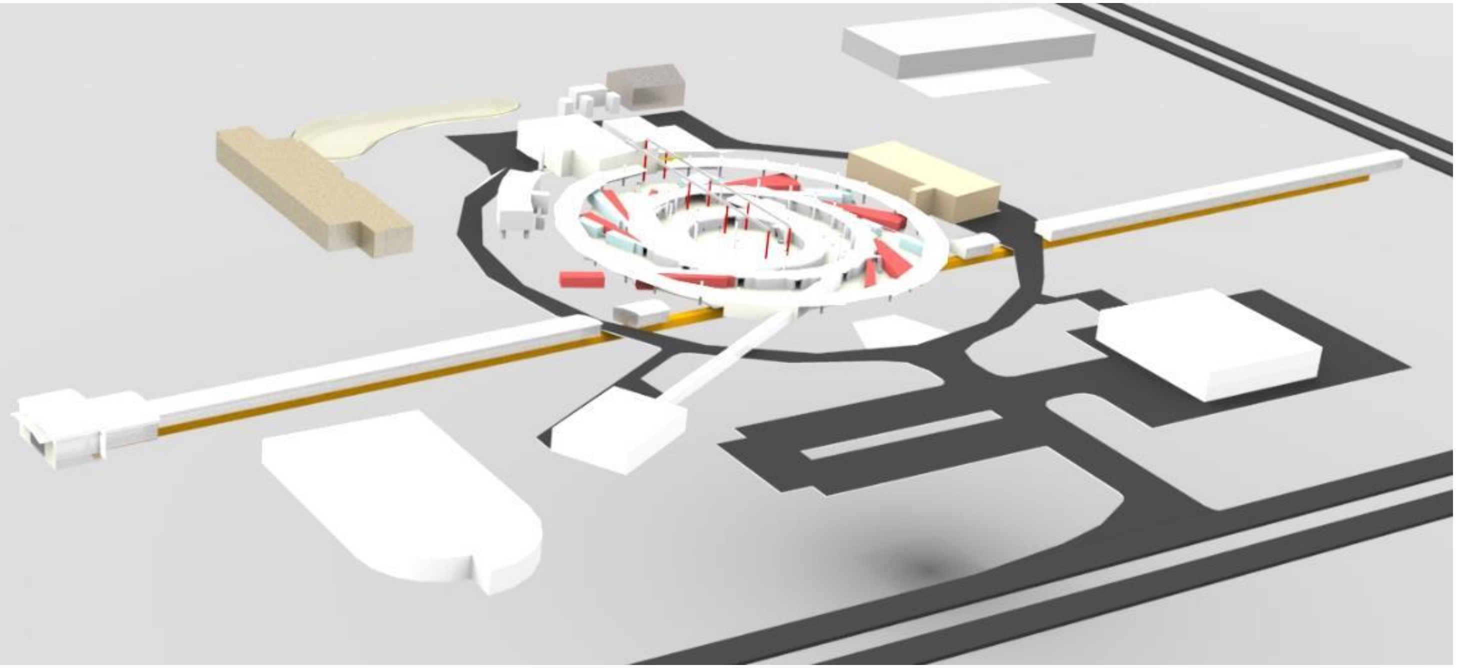
AXXS

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 (6 GeV)

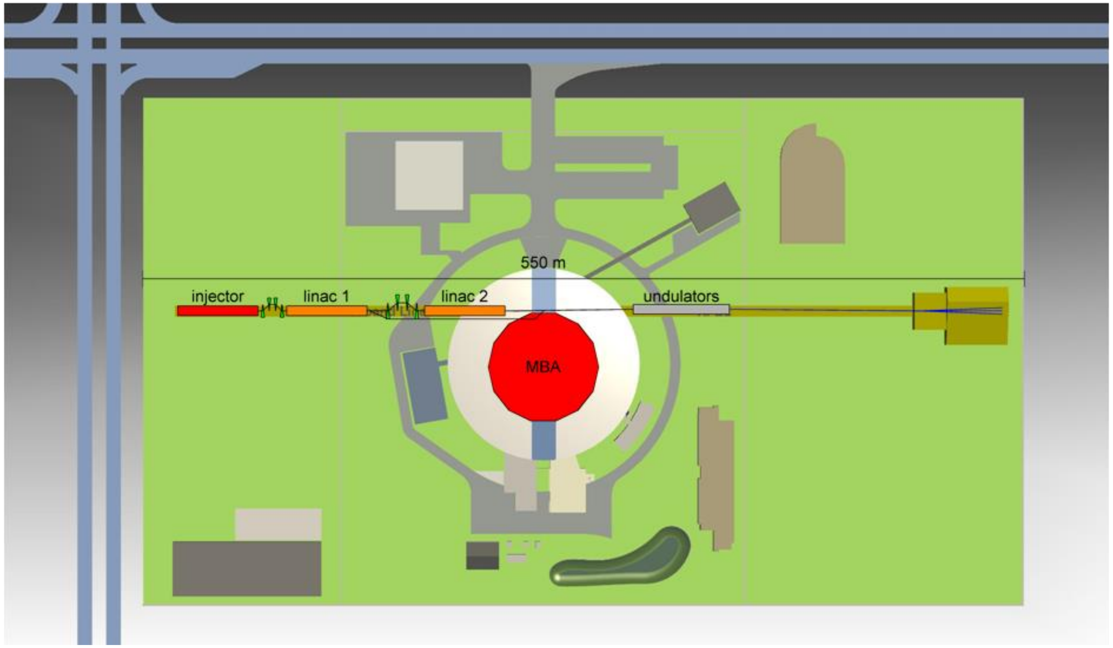


AXXS

- 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

- 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.



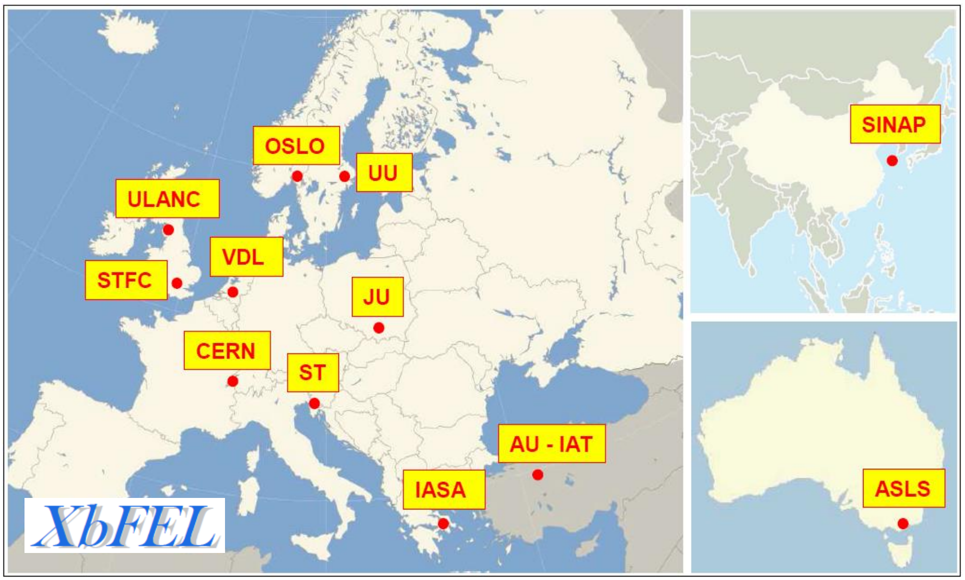
Advanced Accelerator R&D at Melbourne Uni

- Propose new X-band accelerator lab in the old 35 MeV betatron lab
- Future RF photocathode development

The XbFEL Collaboration

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

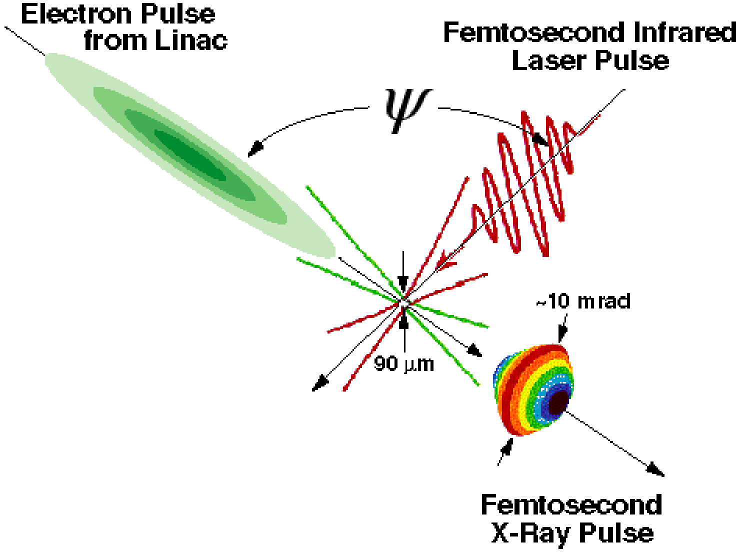
http://xbandfel.web.cern.ch/



ST *Elettra - Sincrotrone Trieste, Italy.*
CERN *CERN Geneva, Switzerland.*
JU *Jagie*
STFC *Dares*
SINAP *Shan*
VDL *VDL E*
OSLO *Unive*
IASA *Natio*
UU *Upps*
ASLS *Australian Synchrotron, Clayton, Australia.*
UA-IAT *Institute of Accelerator Technologies, Ankara, Turkey.*
ULANC *Lancaster University, Lancaster, UK.*

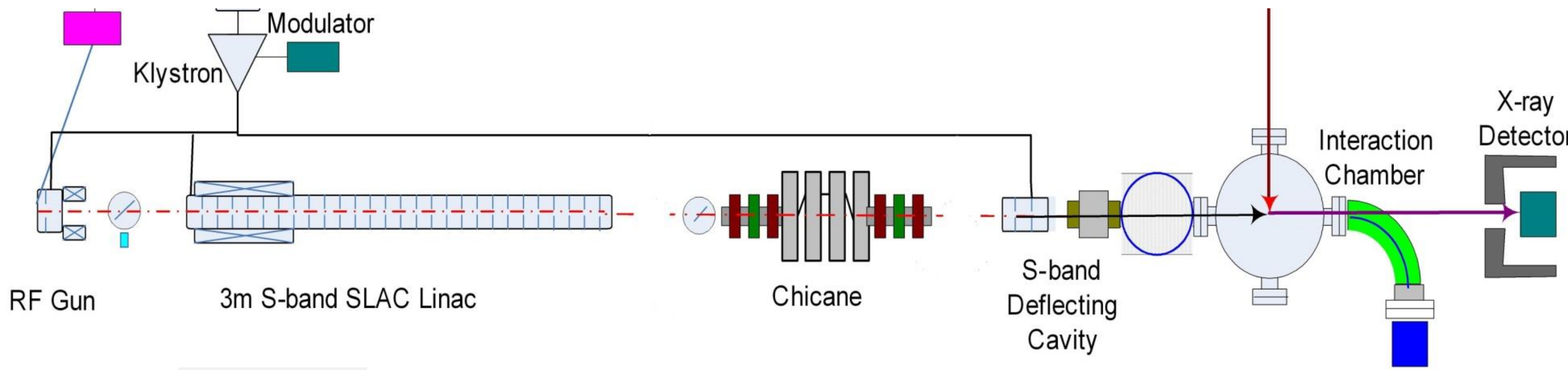
Organizational meeting for second try tomorrow afternoon at 17:30

Tsinghua Thomson-Scattering X-ray

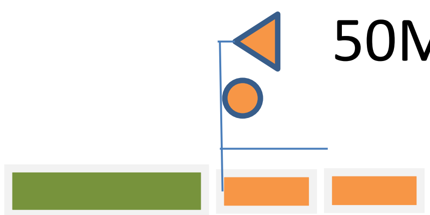


Electron beam	
Energy	45MeV
Bunch length	1~4ps
Charge	~0.7nC
Beam size	30x25um

TTX linac upgrade proposal



1~2 year  1.5m x30MV/m



50MW

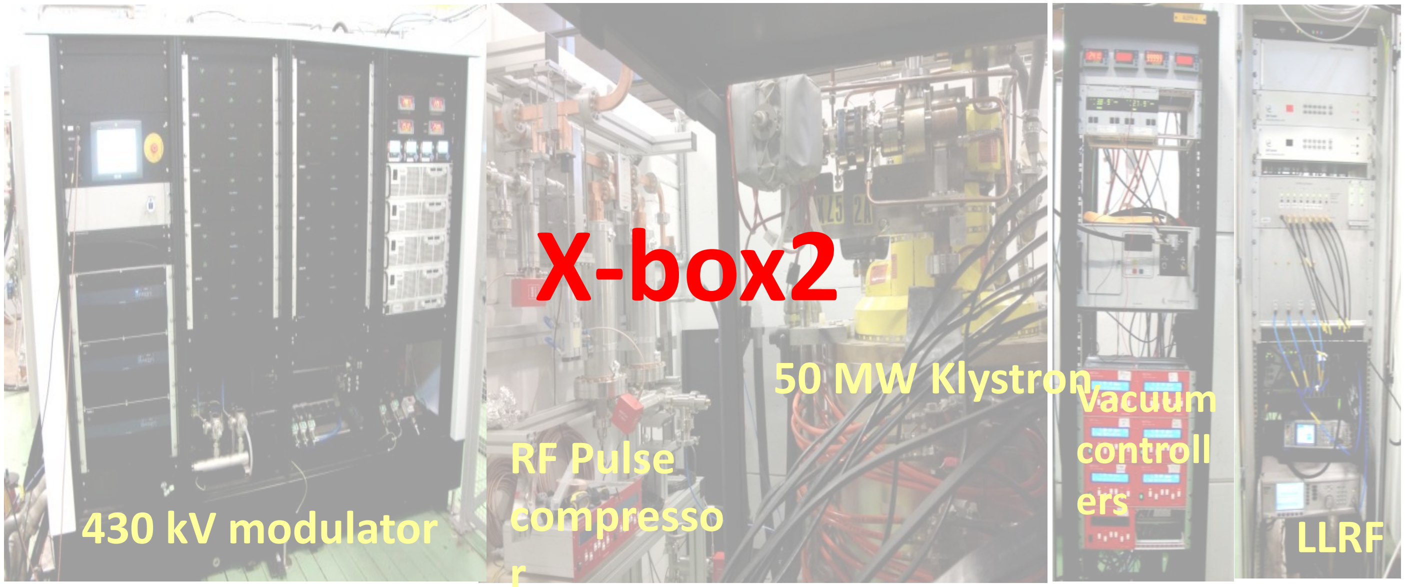
3~5 year 1.5m x 30MV/m + 2 x 0.6m x 75MV/m

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

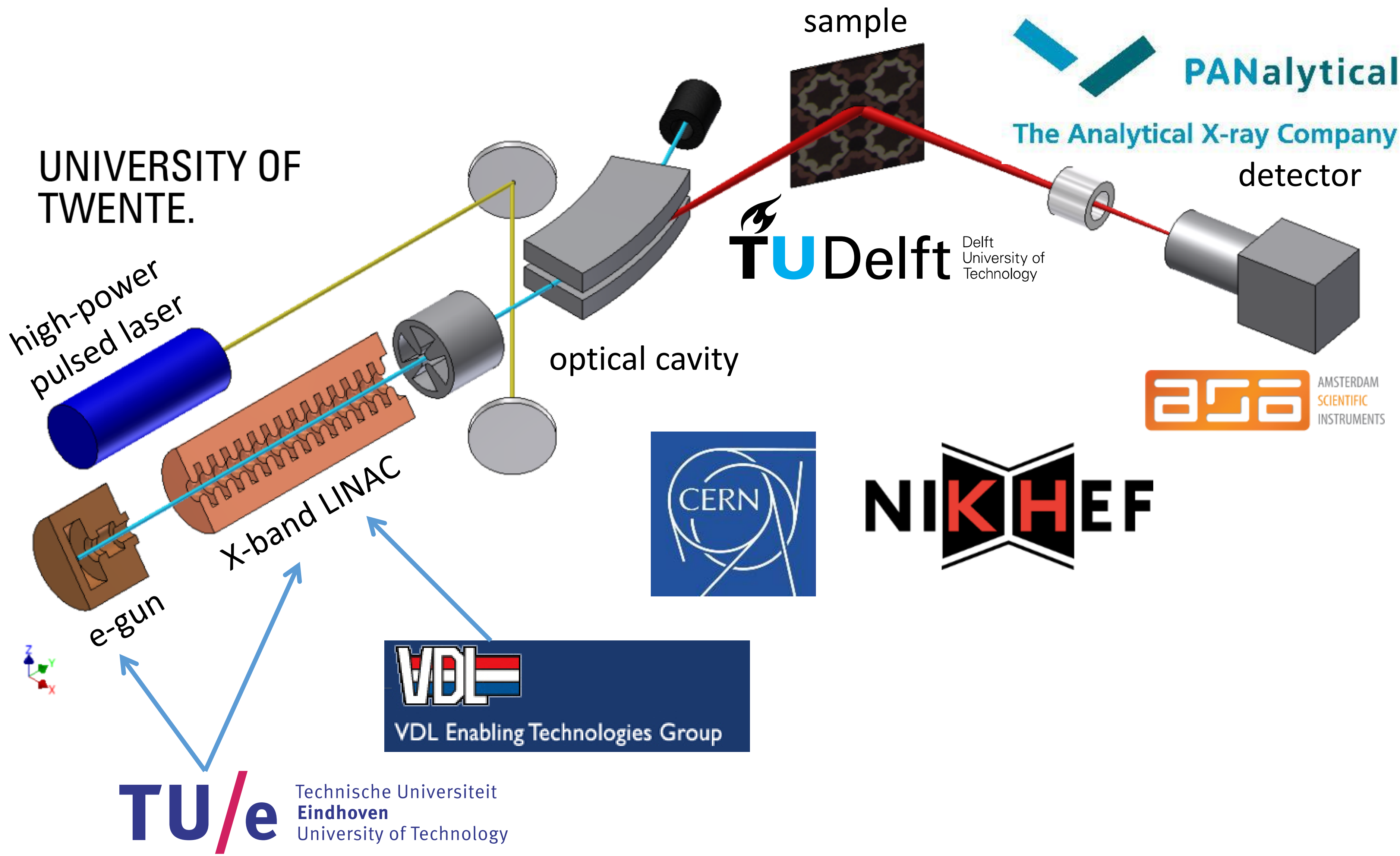
Add X-band to the enerty ~150MeV

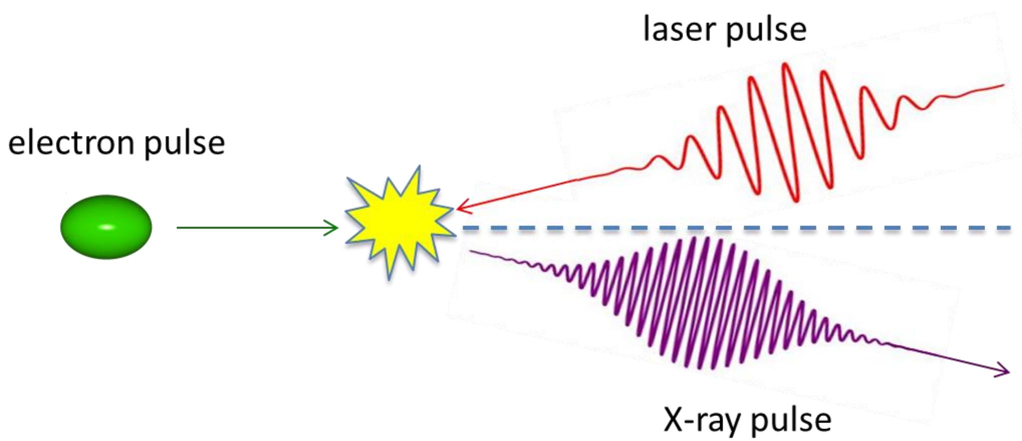
Progress

- Ordered
  - 50MW CPI 11.424GHz Klystron
  - Scandinova solid state modulator

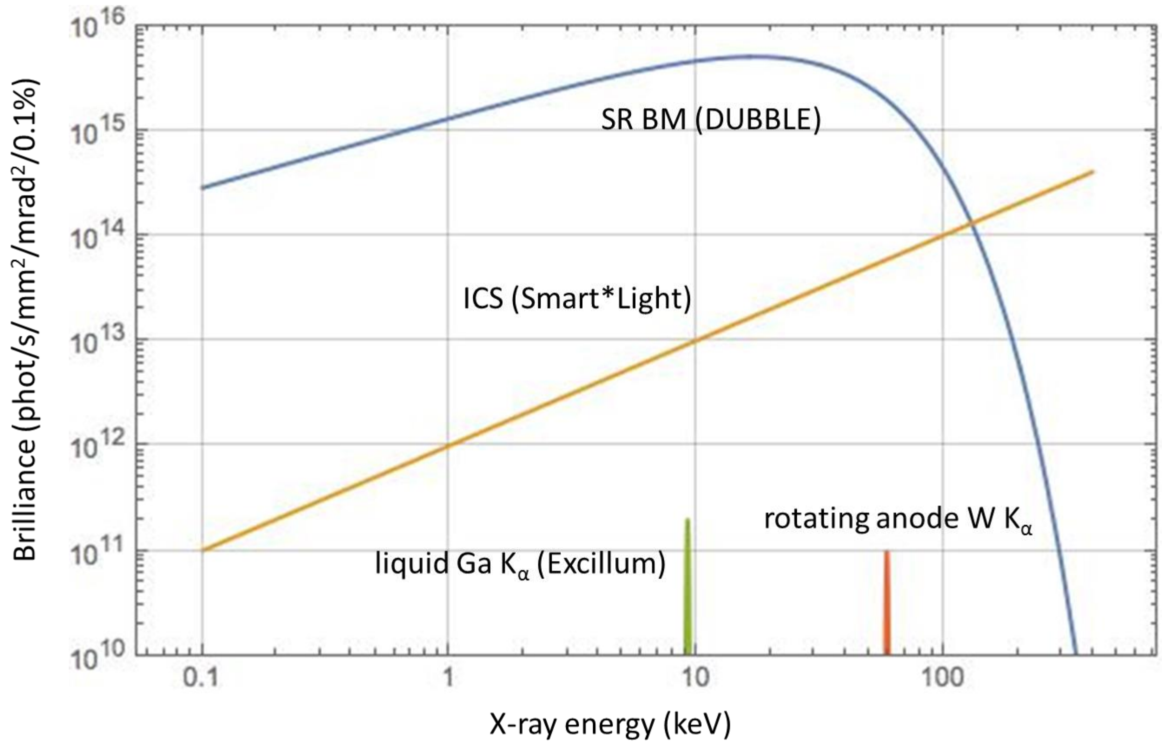


Compton Back Scattering Hard X-Ray Source

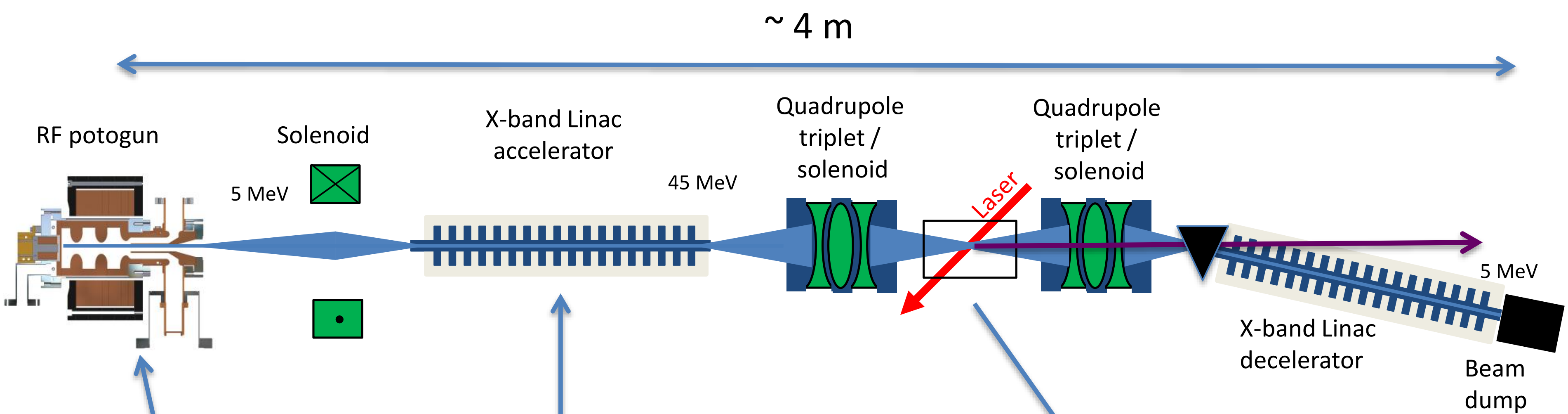




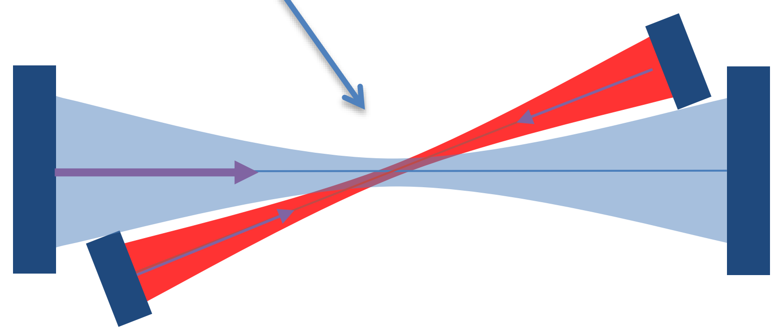
$$I_x = \frac{I_0}{4g^2}(1+g^2q^2)$$



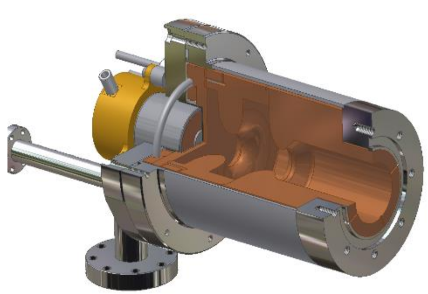
ICS source for hard X-rays

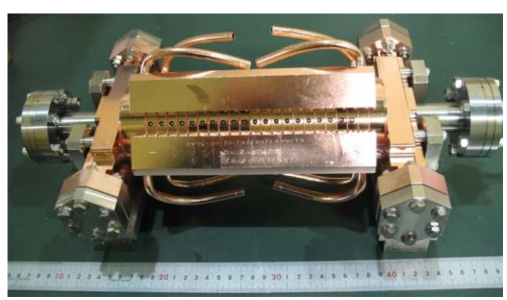


5 MeV RF photogun
Q = 10-100 pC,
ε_n = 0.15-0.5 mm mrad
1 kHz RF pulses
100 bunches/RF pulse

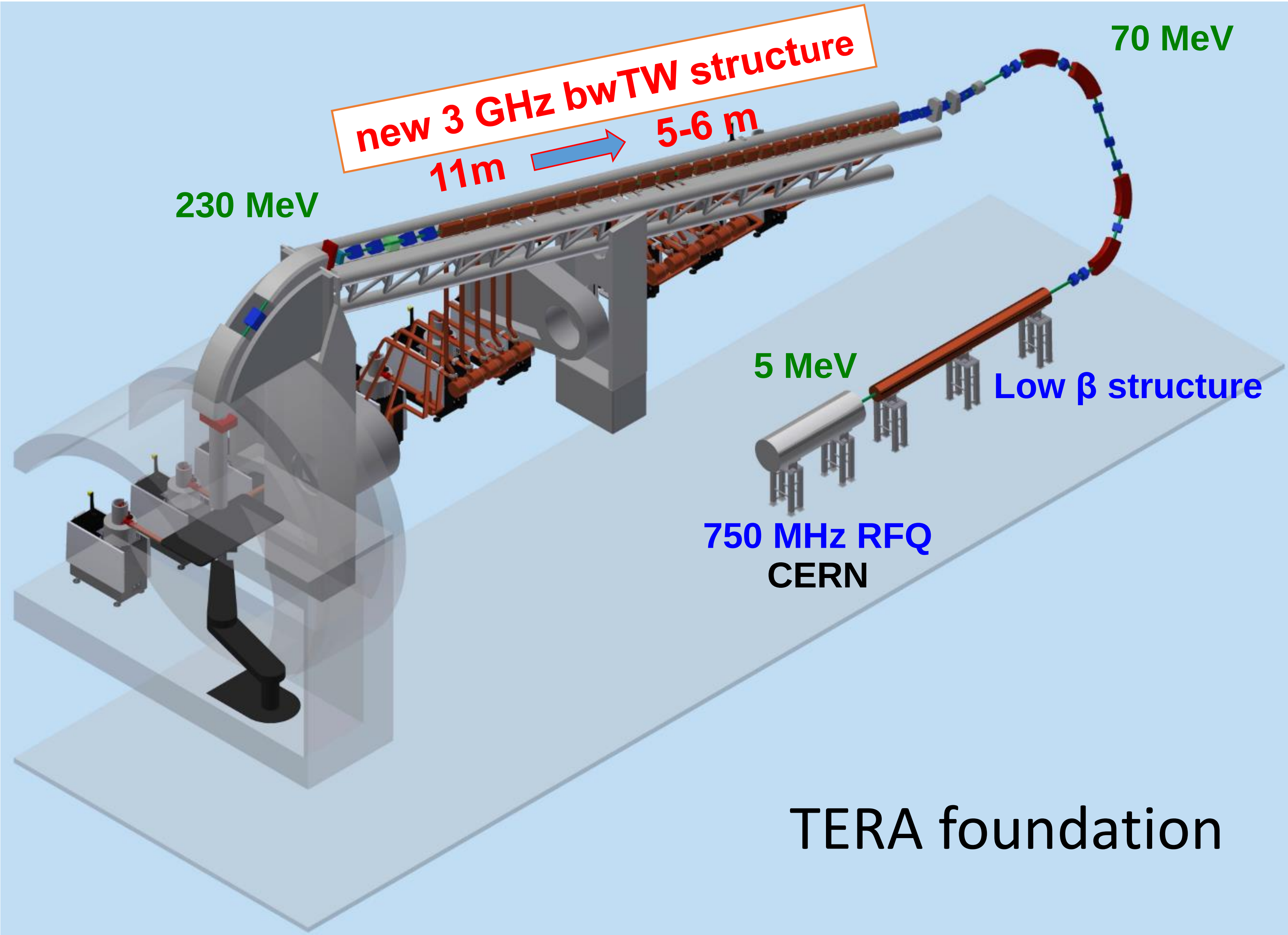


1 kHz, 10 mJ laser
100× recycled in optical cavity
➔10^5 colliding pulses/sec
in 5 µm laser beam waist

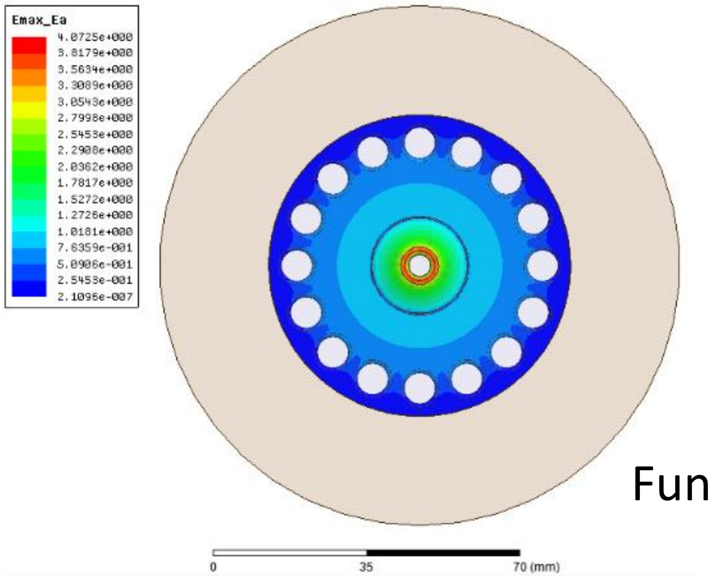




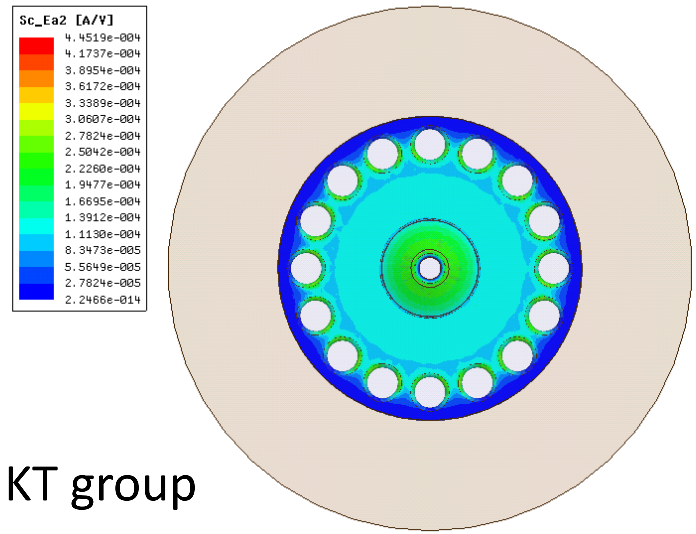
The TULIP Project



RF design and diamond machined disk

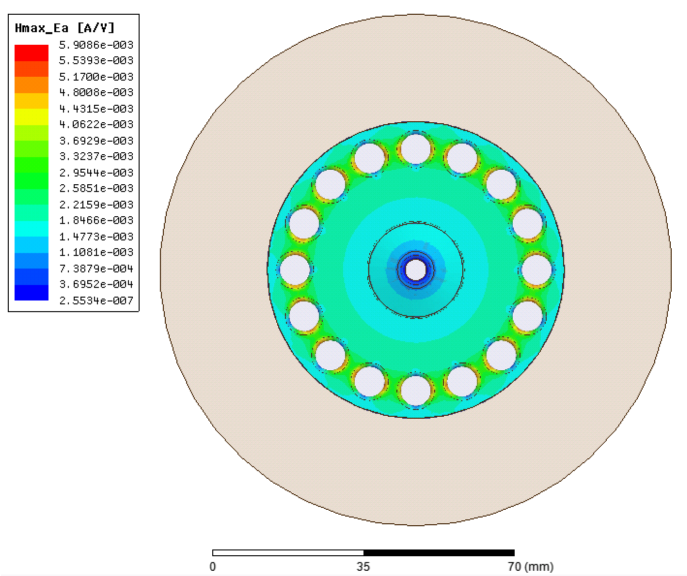


E



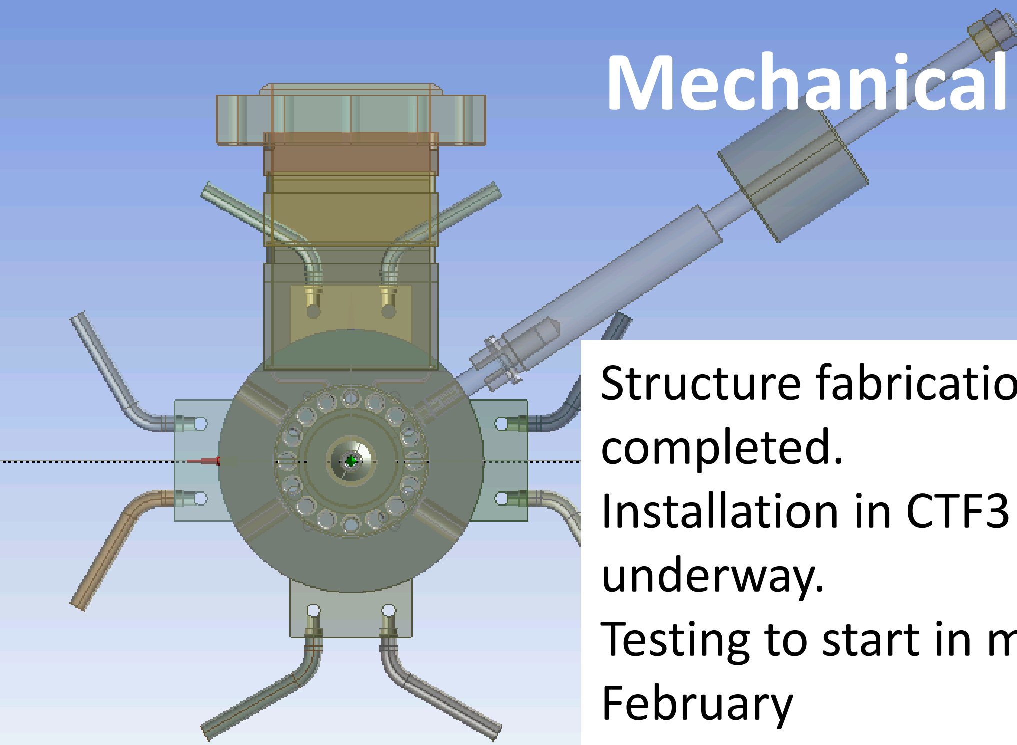
S_c

Funded by CERN KT group



B

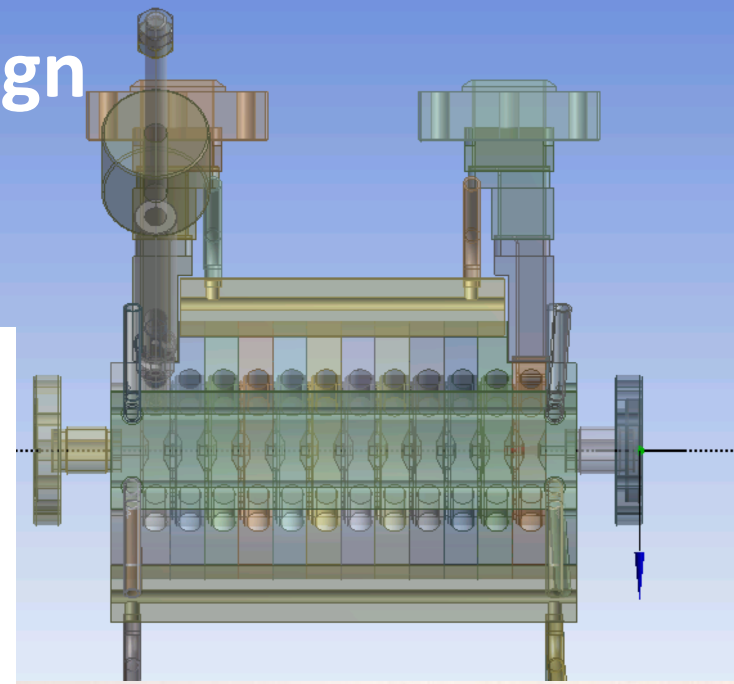
Mechanical design

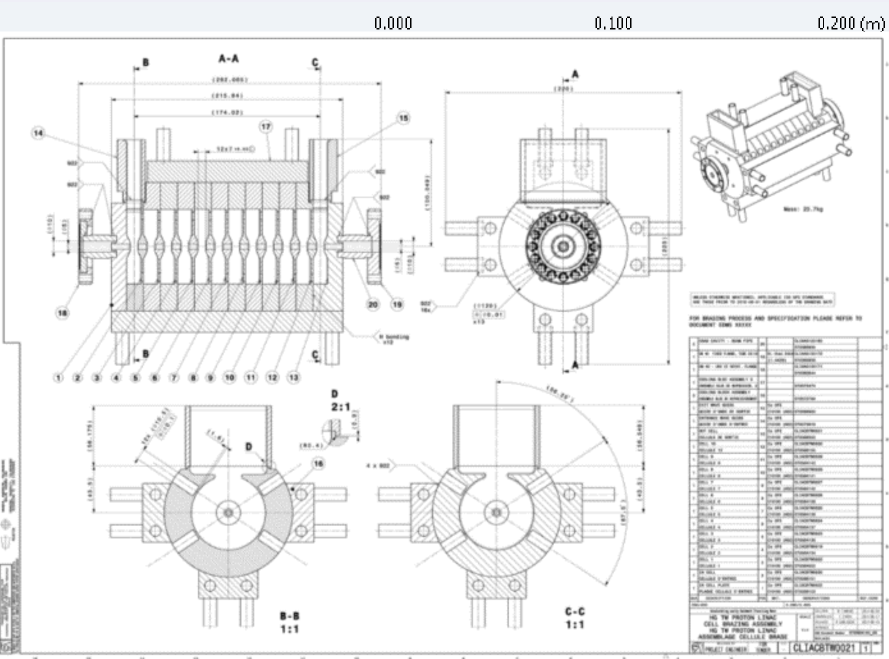


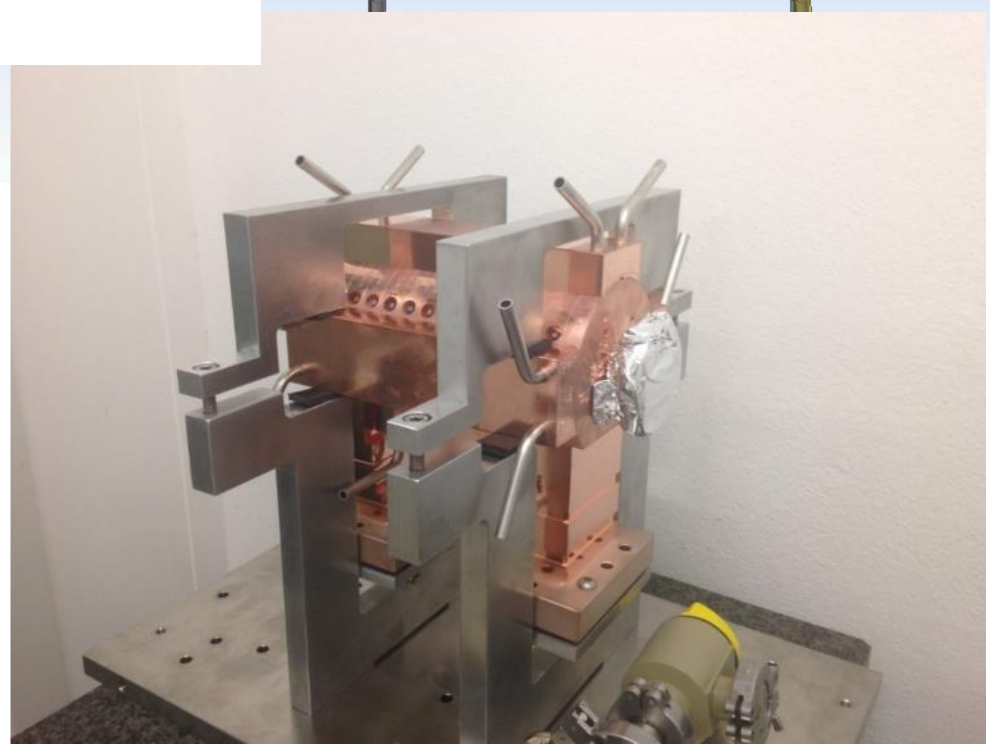
Structure fabrication completed.

Installation in CTF3 underway.

Testing to start in mid-February







Next high-gradient and X-band workshop


International Workshop on Breakdown Science and High Gradient Accelerator Technology (HG2016)

6-8 June 2016
Argonne National Laboratory
US/Central timezone

- Overview
- Timetable
- Registration
  - Registration Form
- List of registrants
- Argonne Visitor Registration Form
- Getting to Argonne
- Previous Meetings
- Accomodations

Support:
nrezek@anl.gov
630-252-2574

We are pleased to announce the 9th workshop on breakdown science and high gradient accelerator technology, HG2016, will be held at Argonne National Laboratory on June 6-8, 2016.

Clearly the identification and advancement of high gradient accelerator technologies for a linear collider have been the main goal since the inception of the High Gradient workshop series. Historically, the workshop has heavily concentrated on progress of X-band accelerator technologies, the area in which the most recent research results have been shared and discussed. The tight collaborations among the participants have pushed practical accelerator technologies to a level that has never been achieved before. Knowledge gained through the HG workshops in the past, like the current depth in understanding RF breakdown, the procedure of fabricating and conditioning high gradient accelerators, and the novel designs of high power rf components, etc., have benefits far beyond the X-band accelerator community.
Besides the intensive focus on X-band high gradient accelerator technologies, the workshop has always made efforts to broaden the spectrum of technologies discussed and attract more talent in related fields. In recent years, the workshop has successfully recruited theorists in material science and experts in accelerator applications, whose participation has significantly enriched the program and generated mutual benefits.
HG2016 will continue this journey. The workshop will share the latest advancements in, but not limited to, breakdown science, high efficiency high power RF sources, low breakdown rate high-gradient accelerators, low cost accelerator fabrication technologies, novel accelerator designs, accelerator

Organizing Committee Members:

https://indico.hep.anl.gov/indico/conferenceDisplay.py?ovw=True&confId=963

My Conclusions

We have a pretty good grip on 100 MV/m.

Quite a number of incremental performance and cost improvements are in the pipeline plus some higher risk/benefit possibilities.

We are rapidly gaining experience running whole klystron-based rf units, with all the details that entails.

Working with other applications is very helpful for all of this.

I would like to acknowledge the contributions of all my colleagues who have carried out all of this work. I didn’t even try to put all the names but I hope I have communicated the excellence of the work and their enthusiasm on everyone's behalf!

Thank you for your attention!