X-Band and High-Gradient à la Carte

CLIC Workshop, 6 February 2014

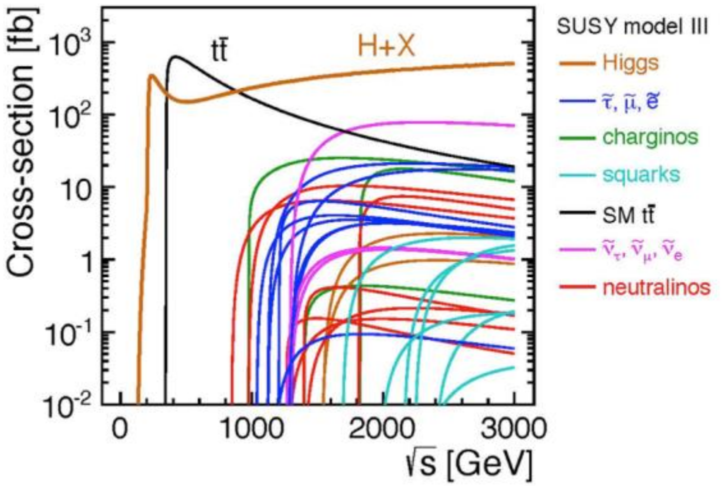
Walter Wuensch, CERN

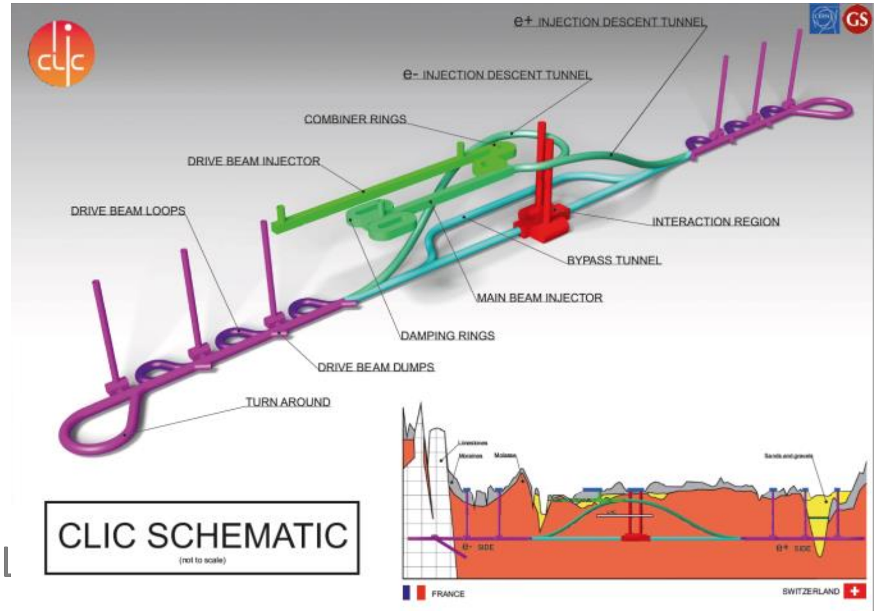
Outline

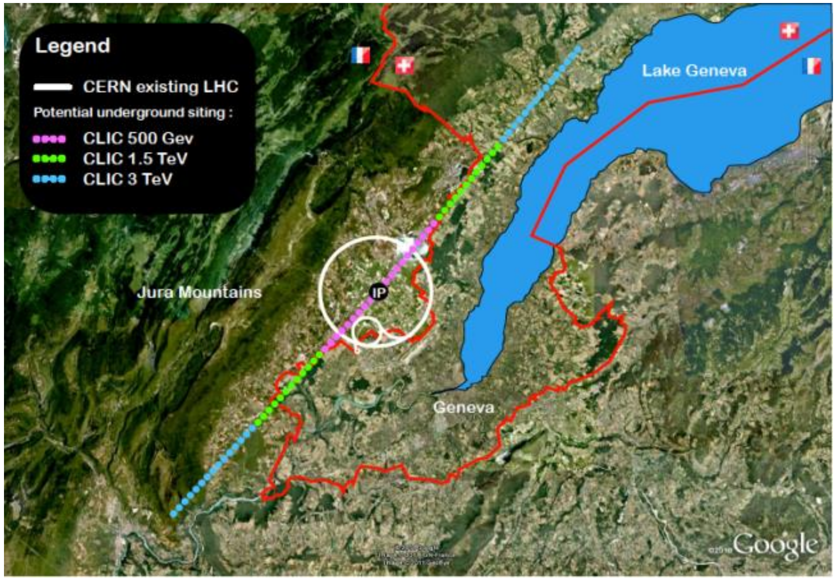
- Background
- Technology
- Optimization
- Applications – all day today!

Introduction

- CLIC is a possible future energy frontier particle physics facility.
- TeV-range e^+e^- linear collider to cover Higgs and new physics which (we hope) will be uncovered in the upcoming full energy LHC run.





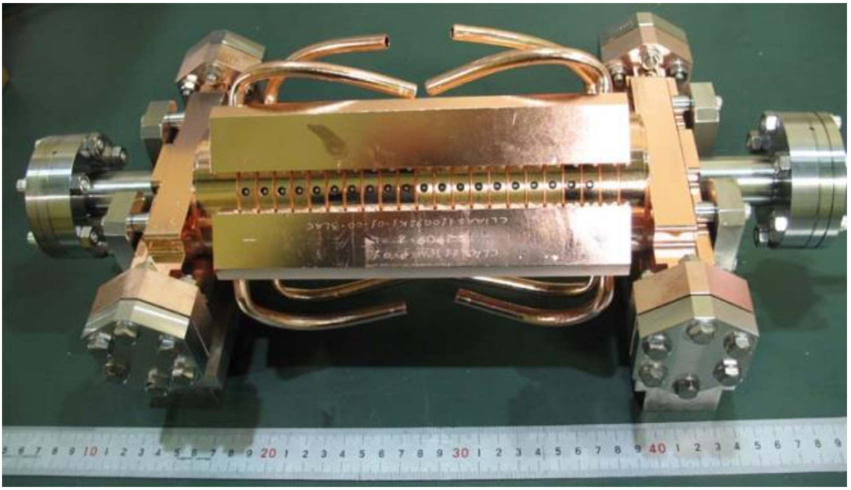


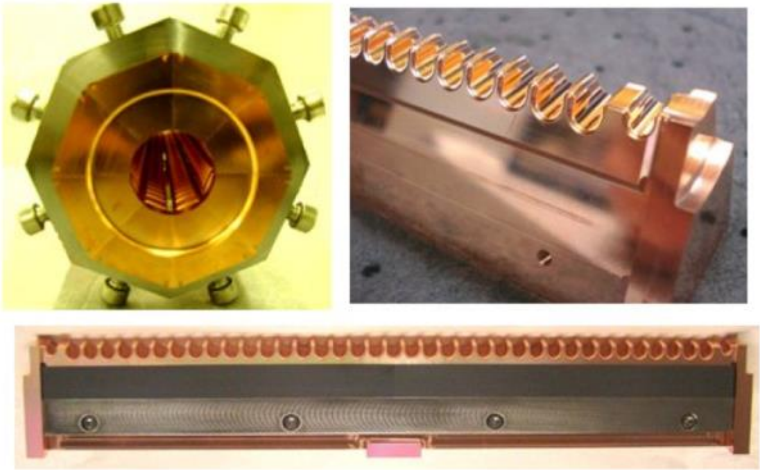
Introduction

During the CDR phase of the CLIC study we developed, and made feasibility demonstrations of, the key technologies for CLIC: high-gradient rf system, rf power generation by drive-beam scheme, low emittance generation and preservation

Focusing on the X-band rf system for the CLIC main linacs:

- **Above 100 MV/m acceleration at low breakdown rate, below 3x10^{-7} breakdowns/pulse/m**
- **Above 134 MW power production**
- **Few-micron level tolerance parts and assembly**
- **Quantitative high-gradient and high-power design capability**





Current Priorities

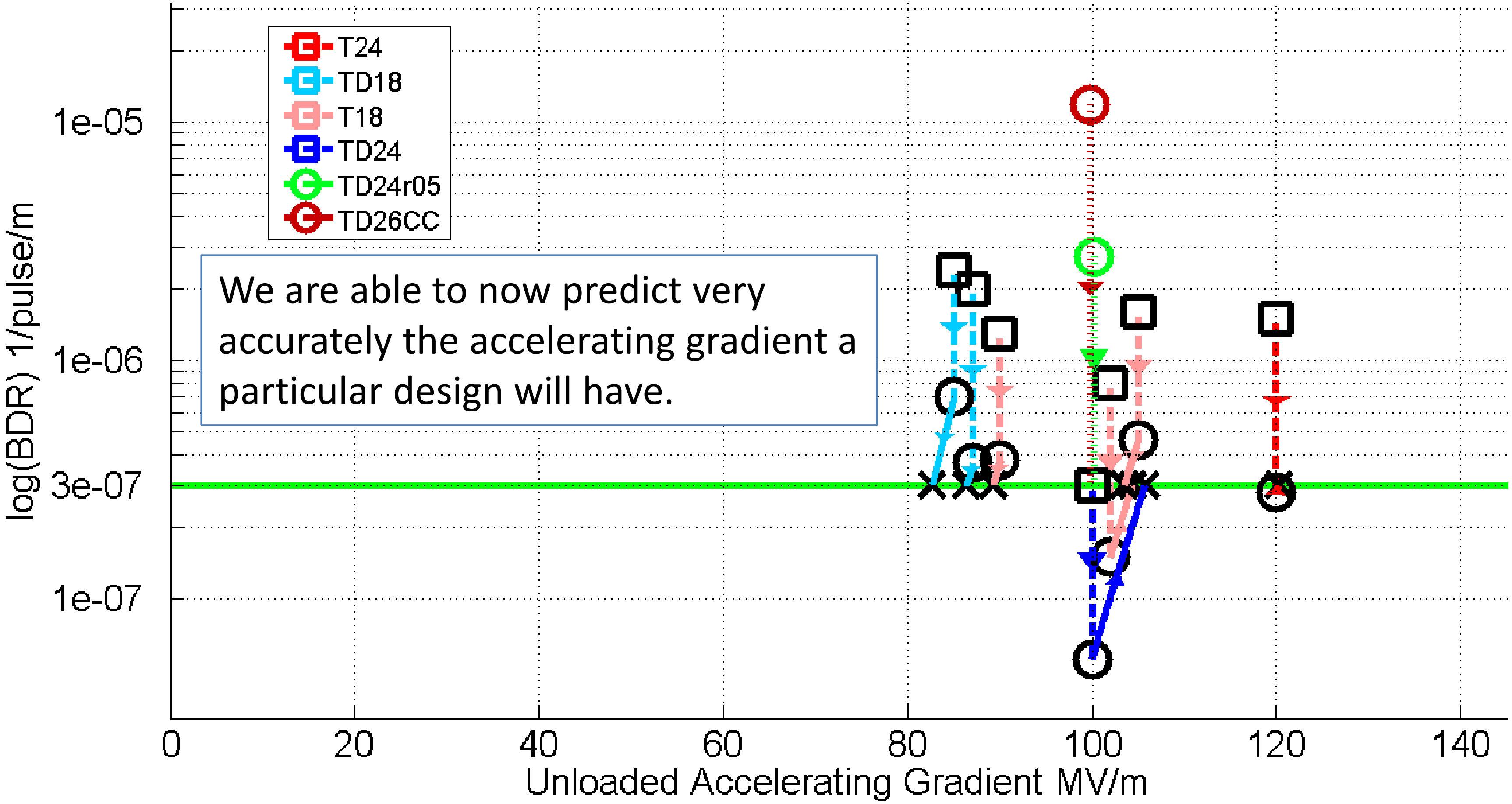
- Consolidate results
- Investigate reproducibility and lifetime
- Re-optimize design
- Optimize fabrication and conditioning
- Industrialize technology

It has become clear that the three red points can be effectively pursued by **actively promoting** the use of X-band and high-gradient technology in other projects.

We also wish give a direct technological return made on the investment made in our project. This is a mandate of CERN.

Accelerating Structures

Accelerating structure performance summary



We are able to now predict very accurately the accelerating gradient a particular design will have.

How we got there: High-power design laws

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

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

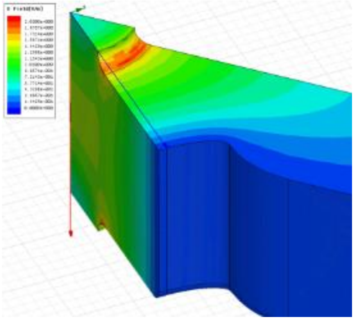
global power flow

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

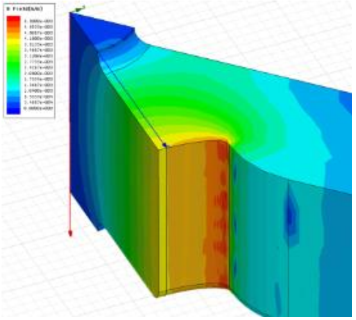
local complex power flow

New local field quantity describing the high gradient limit of accelerating structures.
A. Grudiev, S. Calatroni, W. Wuensch (CERN).
2009. 9 pp.
Published in Phys.Rev.ST Accel.Beams 12 (2009) 102001

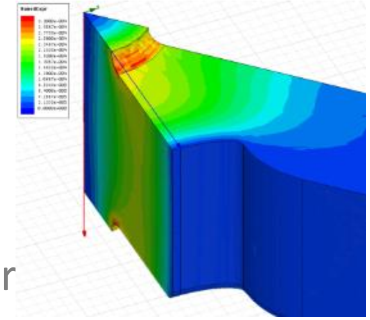
E_s/E_a



H_s/E_a



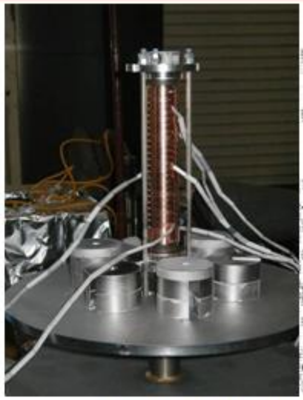
S_c/E_a^2

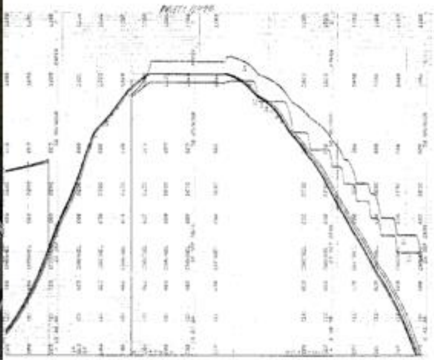


How we got there: heat treatment and material structure

Stacking disks

Diffusion Bonding of T18_vg2.4_DISC





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

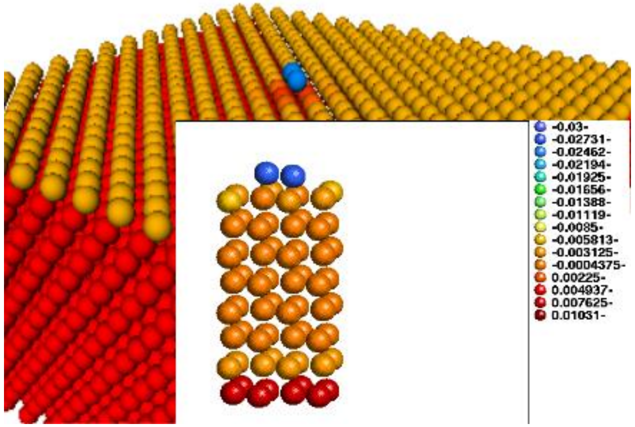
Holding for 1 hour at 1020° C

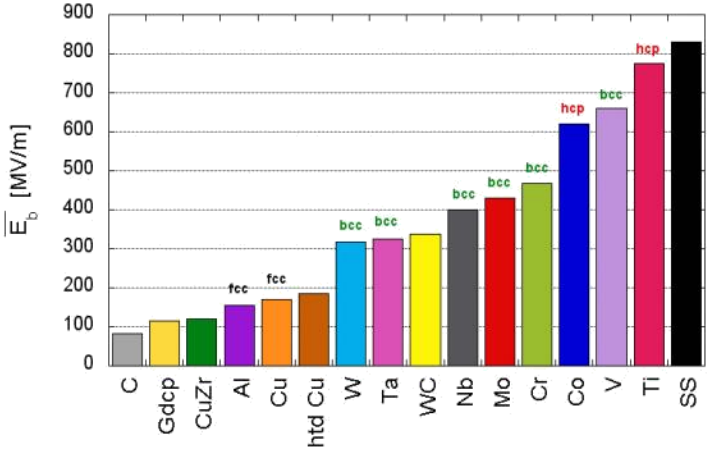
Vacuum Baking of T18_vg2.4_DISC

650° C

10 days

Temperature treatment for high-gradient developed by NLC/JLC



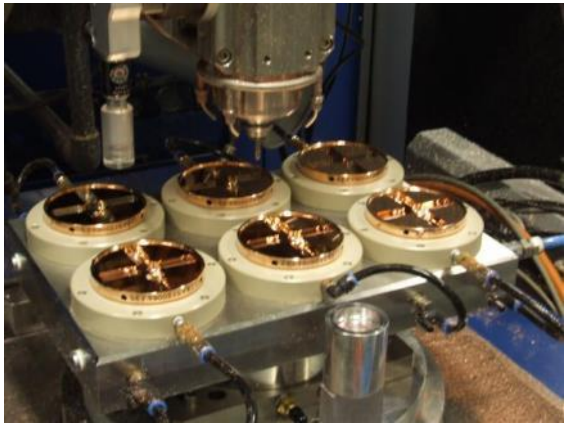


Significant progress to *understand* why it works.

Micron precision turning and milling

- Accelerating structure tolerances drive transverse wakefields and off-axis rf induced kicks which in turn leads to emittance growth – micron tolerances required.
- Multi-bunch trains require higher-order-mode wakefield suppression – cells require milled features.
- High-speed diamond machining also seems to be beneficial for high-gradient performance through minimizing induced surface stresses.

Development done
“in industry”



Klystron-based Test Stands

CLIC and X-band klystrons

CLIC rf power generation is by the two-beam scheme, major feasibility demonstrations have been made in CTF3.

But we need to complement CTF3 with more, and higher repetition rate, klystron based test stands to support the accelerating structure development program.

We will have three:

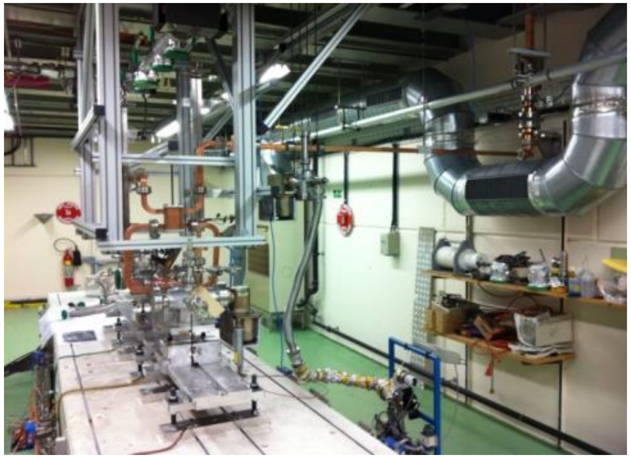
- Xbox-1 – Operational, powered by SLAC XL-5, 50 MW, 1.5 μs, 50 Hz.
- Xbox-2 – Nearing completion, powered by CPI VKX-8311A, 50 MW, 1.5 μs, 50 Hz.
- Xbox-3 – Major orders placed, powered by Toshiba E37113, 6 MW, 5 μs, 400 Hz.

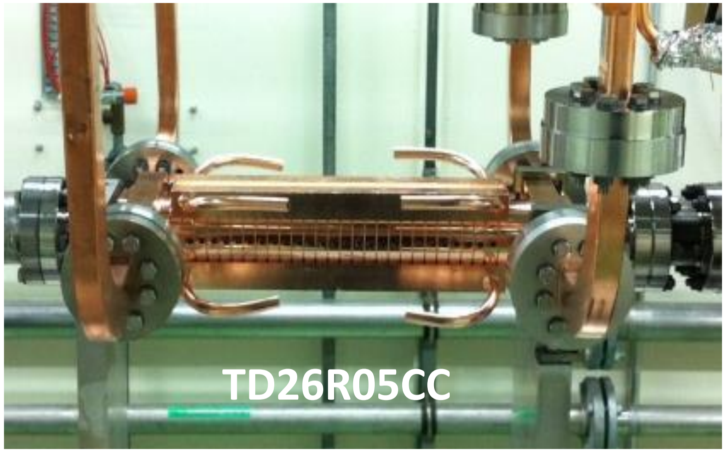
Now it turns out that these three test stands resemble the rf power units for a wide range of **high gradient** and **high repetition rate** electron linac designs.

We will try to exploit this similarity with you in a spirit of mutual interest.

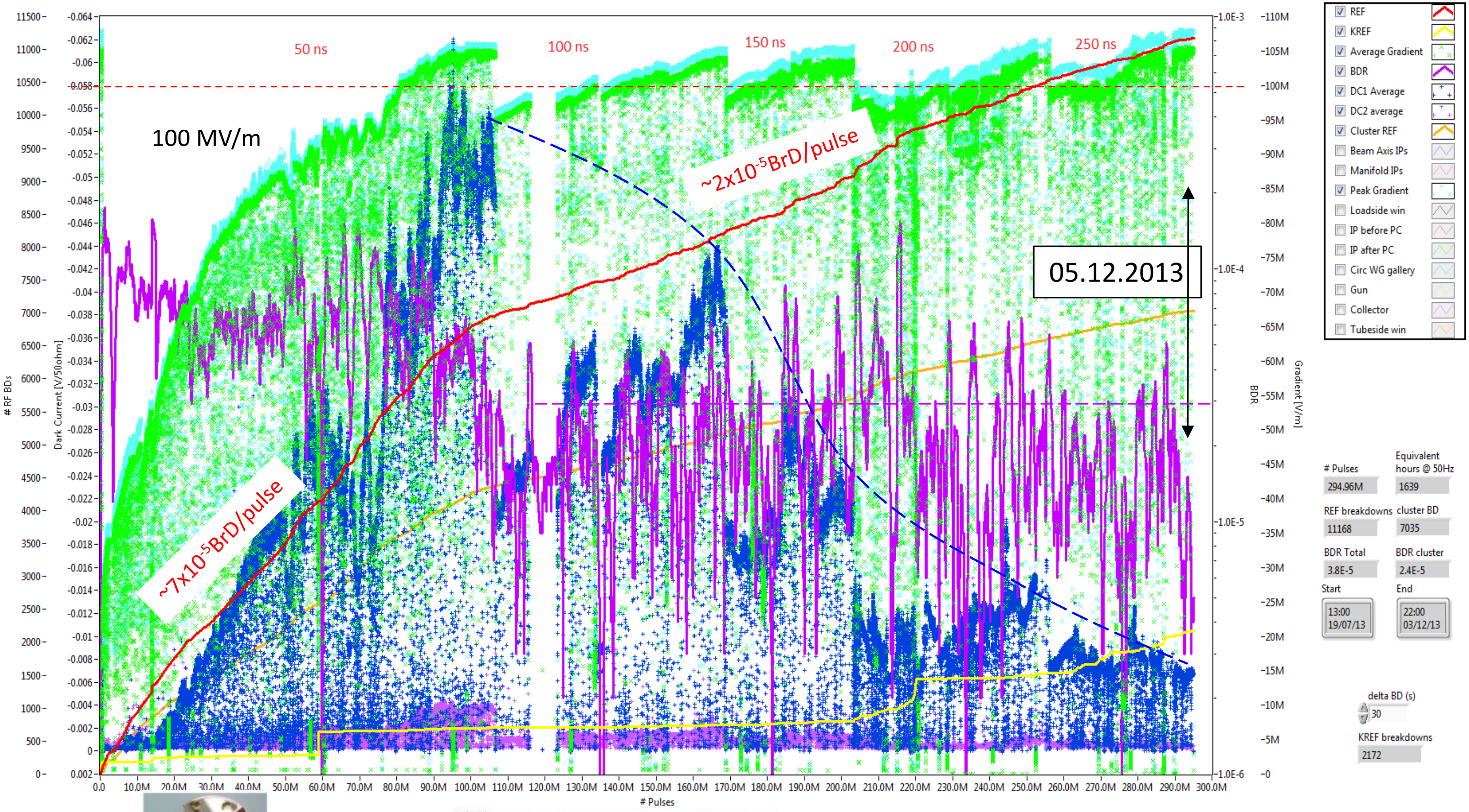
XBOX1 is up and running for almost 1.5 year

SLAC XL-5 klystron.





TD26R05CC



100 MV/m

~2x10^{-5}BrD/pulse

~7x10^{-5}BrD/pulse

05.12.2013

- ☑ REF
- ☑ KREF
- ☑ Average Gradient
- ☑ BDR
- ☑ DC1 Average
- ☑ DC2 average
- ☑ Cluster REF
- ☐ Beam Axis IPs
- ☐ Manifold IPs
- ☑ Peak Gradient
- ☐ Loadside win
- ☐ IP before PC
- ☐ IP after PC
- ☐ Circ WG gallery
- ☐ Gun
- ☐ Collector
- ☐ Tubeside win

# Pulses	Equivalent hours @ 50Hz
294.96M	1639

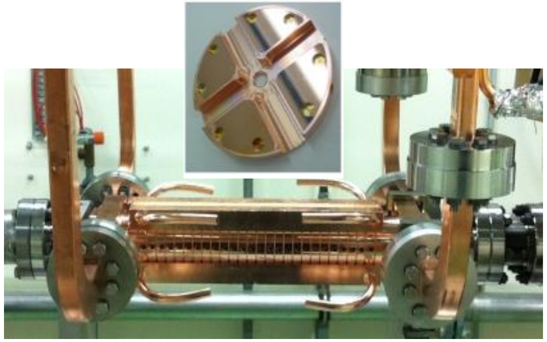
REF breakdowns	cluster BD
11168	7035

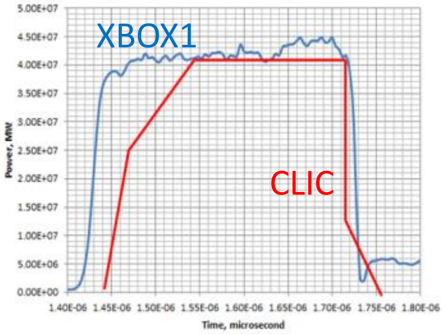
BDR Total	BDR cluster
3.8E-5	2.4E-5

Start	End
13:00 19/07/13	22:00 03/12/13

delta BD (s): 30

KREF breakdowns: 2172





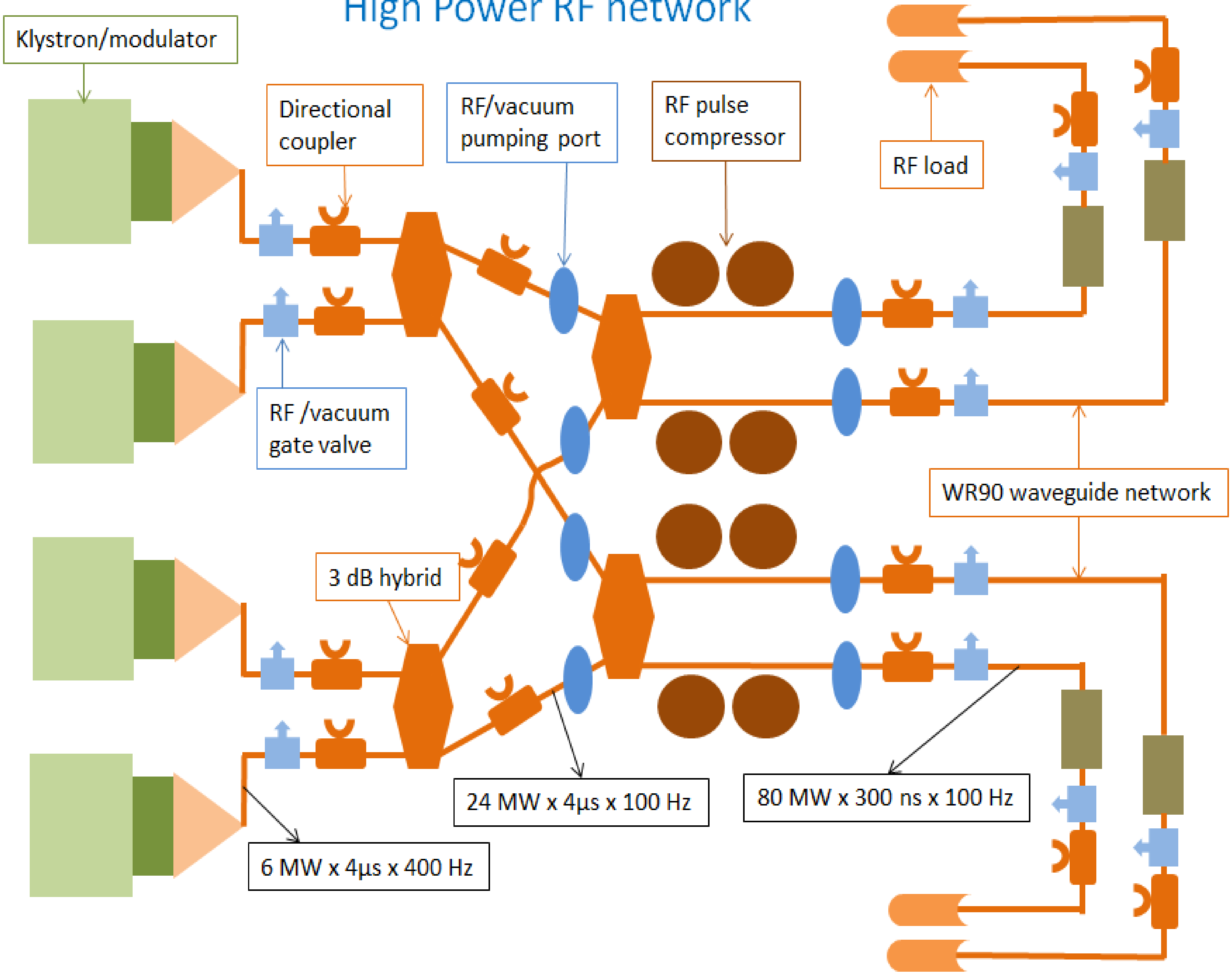
Full-fledged CLIC accelerating structure **TD26R05CC** build by CERN is successfully processed in XBOX1 up to 107 MW/m unloaded accelerating gradient at 250 ns pulses . We have started now study of breakdown rate evolution at the fixed (100 MV/m) gradient.

XBOX2 area, 06.12.2013

The first commercial (CPI) 50 MW 12 GHz klystron. Klystron processing at SLAC is completed. Tube will be shipped to CERN at the end of January 2014 after acceptance at SLAC with CERN representatives.

CPI klystron acceptance testing at SLAC, with PSI, Trieste and CERN

High Power RF network



Klystron/modulator

Directional coupler

RF/vacuum pumping port

RF pulse compressor

RF load

RF /vacuum gate valve

WR90 waveguide network

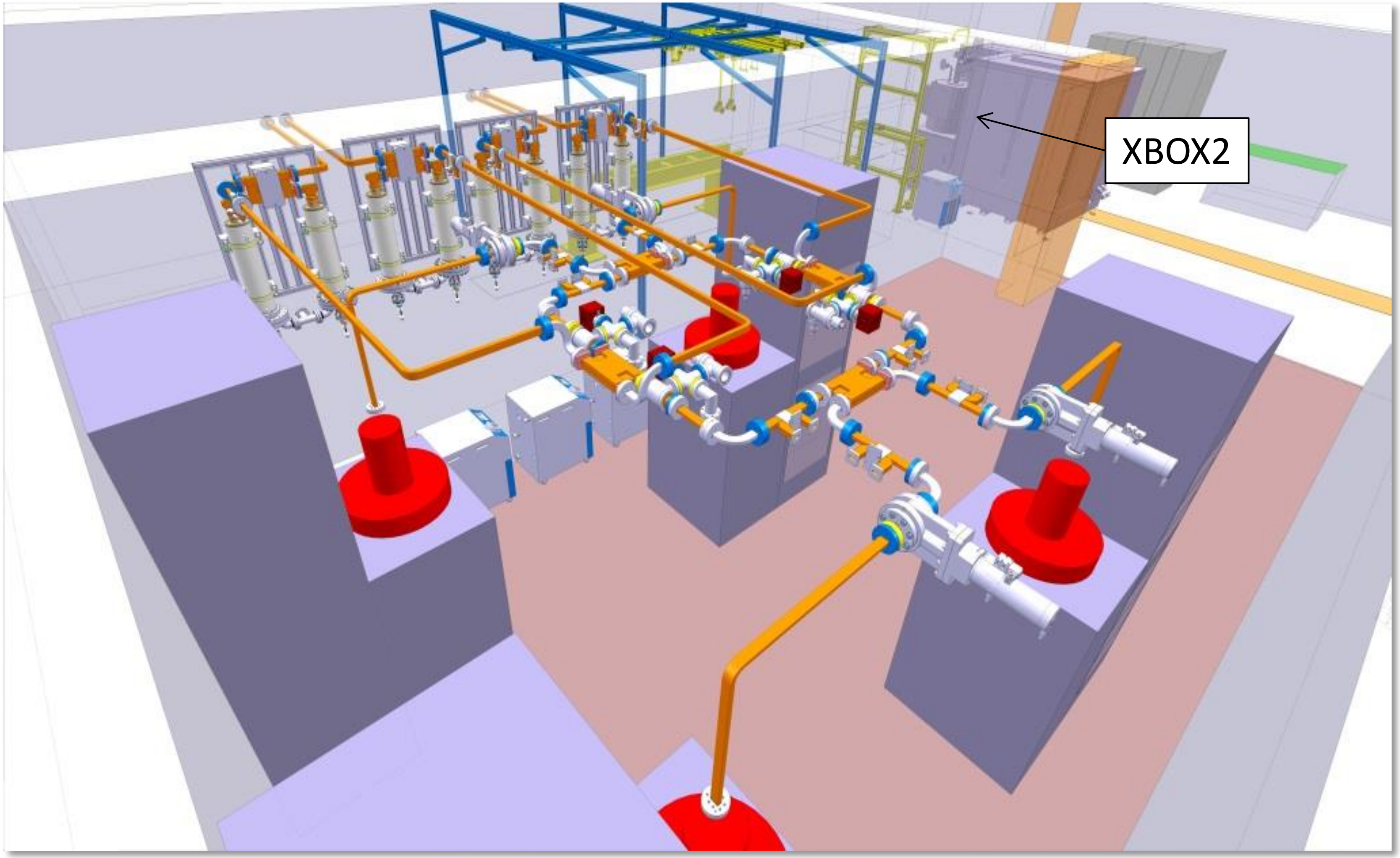
3 dB hybrid

24 MW x 4μs x 100 Hz

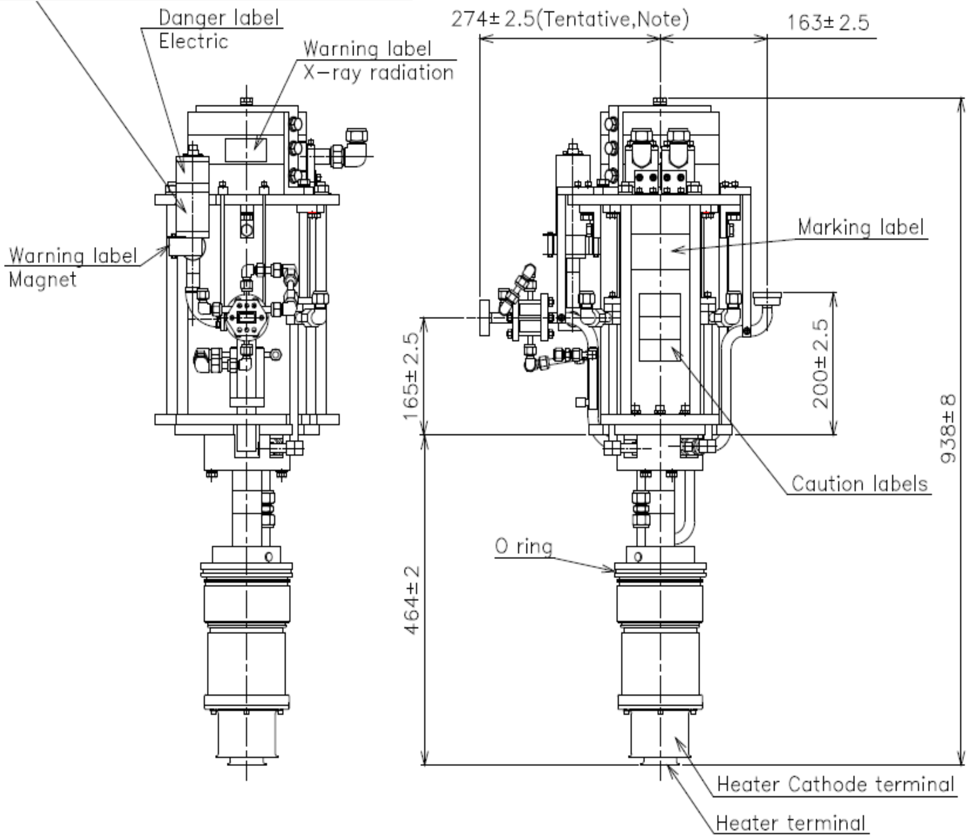
80 MW x 300 ns x 100 Hz

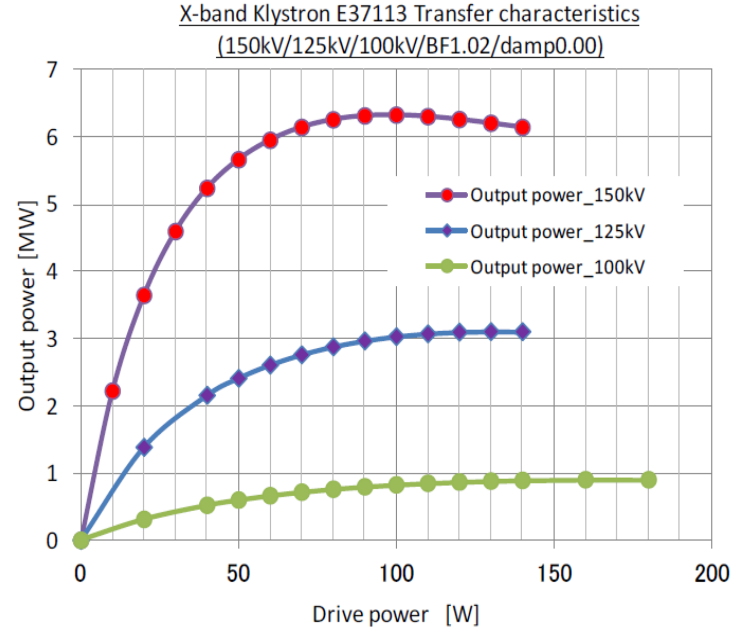
6 MW x 4μs x 400 Hz

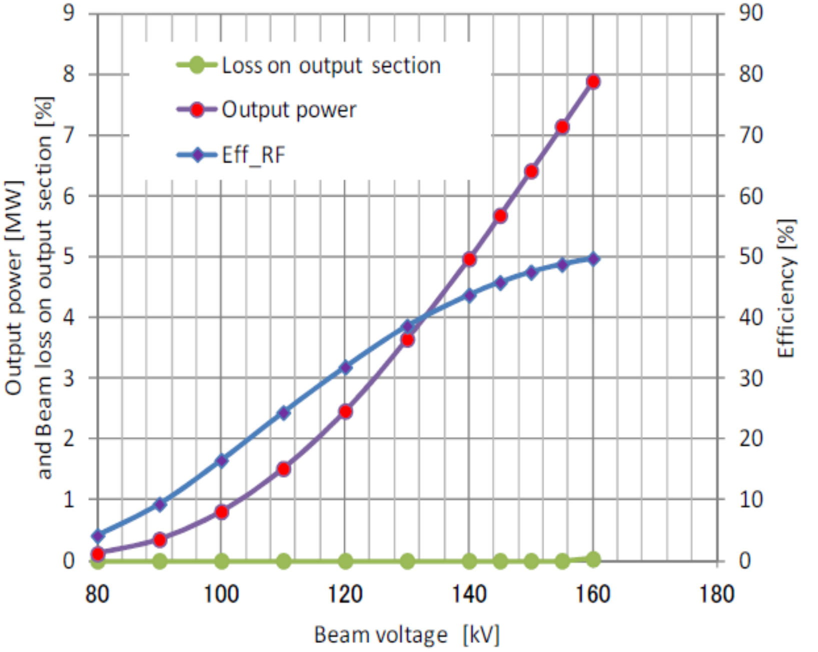
3D layout/integration of XBOX3



Peak power: 6 MW
Beam Voltage: 150 kV
Beam current: 90 A
Average power: 12.4 kW
Efficiency: 47.5%




X-band Klystron E37113 Transfer characteristics (150kV/125kV/100kV/BF1.02/damp0.00)



- 4 turn-key 6 MW, 11.9942 GHz power stations (klystron/modulator) have been ordered from industry.
- The first unit is scheduled to arrive at CERN in October 2014. The full delivery will be completed

Modified K1 ScandiNova modulator

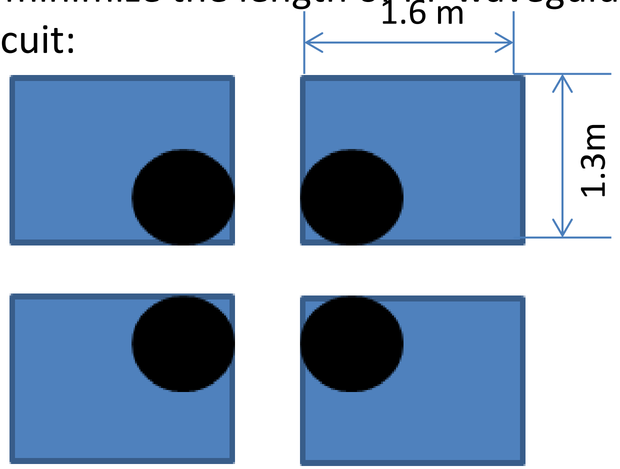
ScandiNova

The illustration of new 2 cabinet concept that will be adopted for 6 MW Toshiba klystrons.

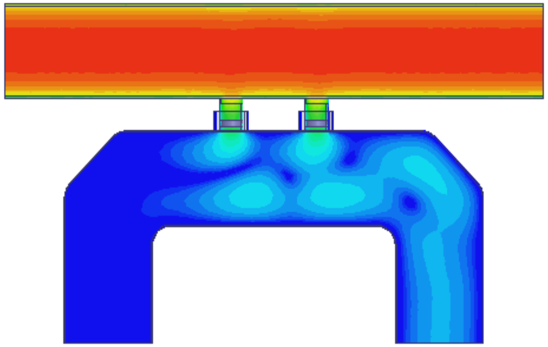
Modulator parameters (max.)
for 6 MW Toshiba klystron

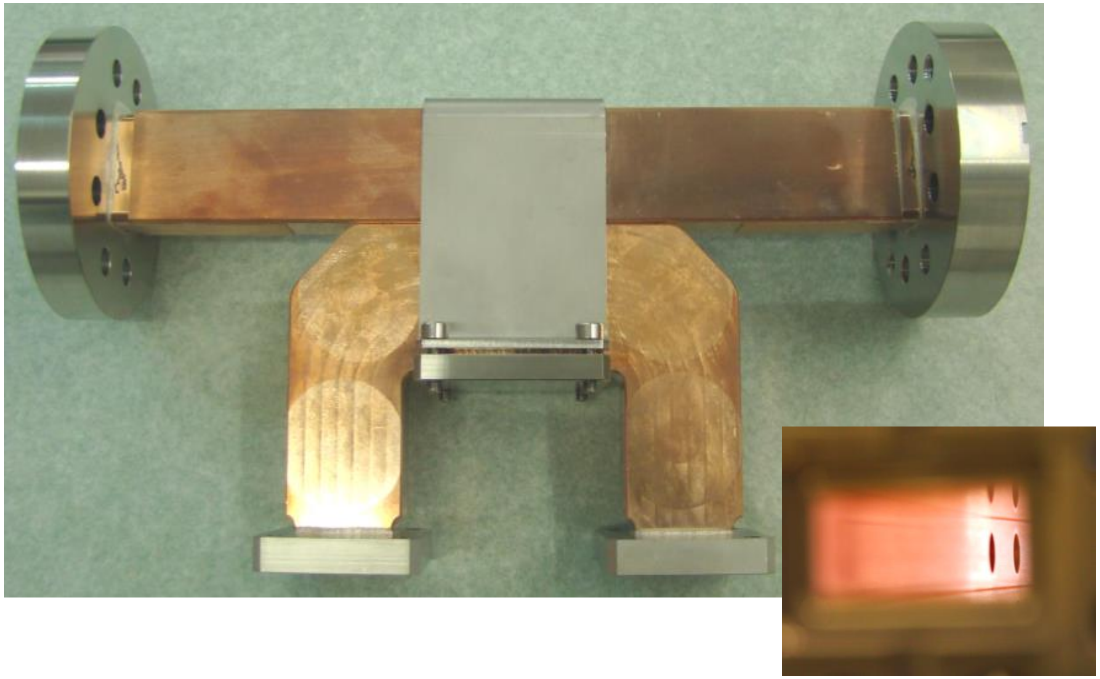
Peak RF power: 8.0 MW
Pulsed voltage: 175 kV
Pulse current: 115 A
Average power: 50 kW
Pulse length (flat): 5µsec
Rep. rate: 400 HZ

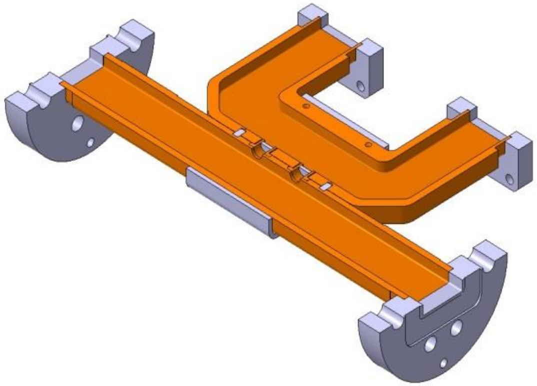
- Doubled width oil tank. To facilitate installation of the Toshiba klystron which has rather wide (∅ 0.7 m) solenoid.
- Additional cabinet (comes for free). It can be used for Klystron RF driver amplifier, Solenoid PS, Ion Pump PS etc.
- New Control System that will simplify integration of external parts and offer a lot of new features.
- Flexible design (klystrons positioning) to minimize the length of RF waveguide circuit:

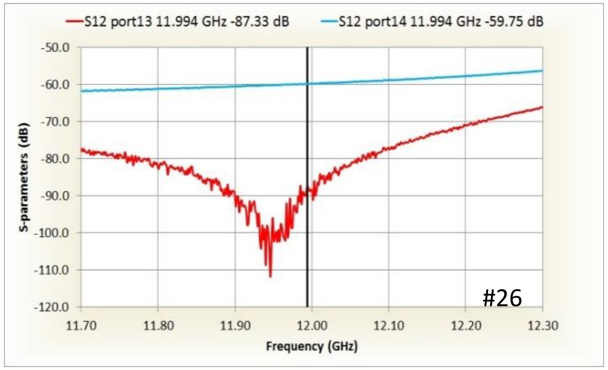


‘Simple’ -60 dB directional coupler









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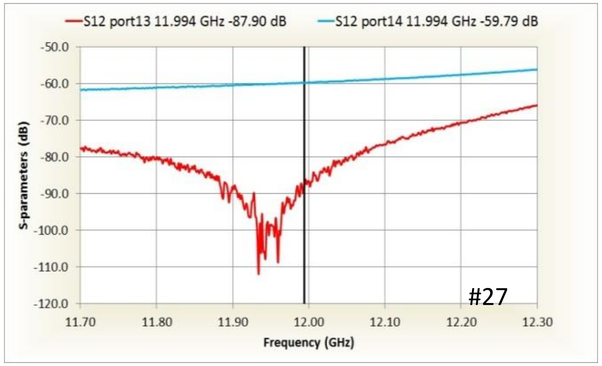

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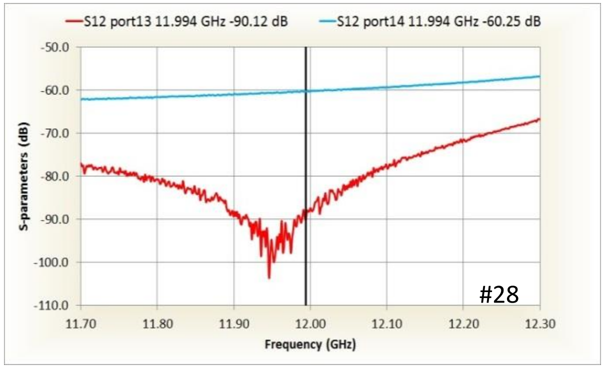
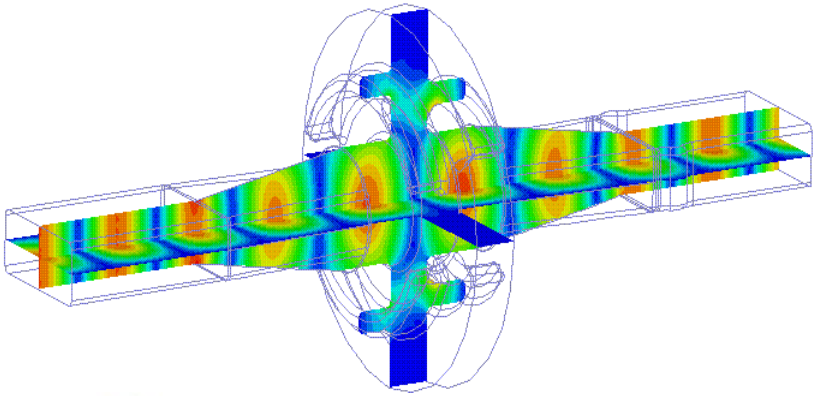
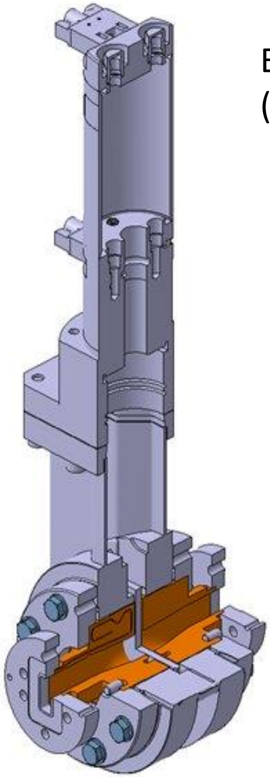


#28

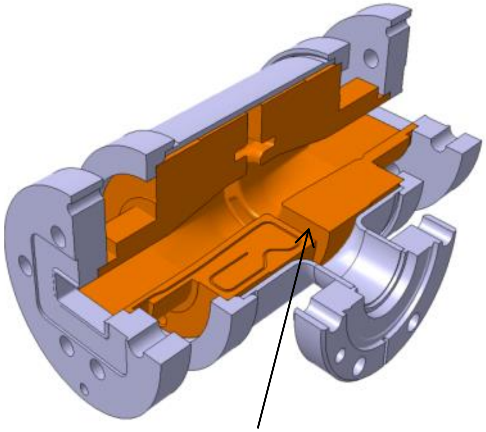
Compact RF/vacuum gate valve and vacuum pumping port

Doubled-choke WG joint

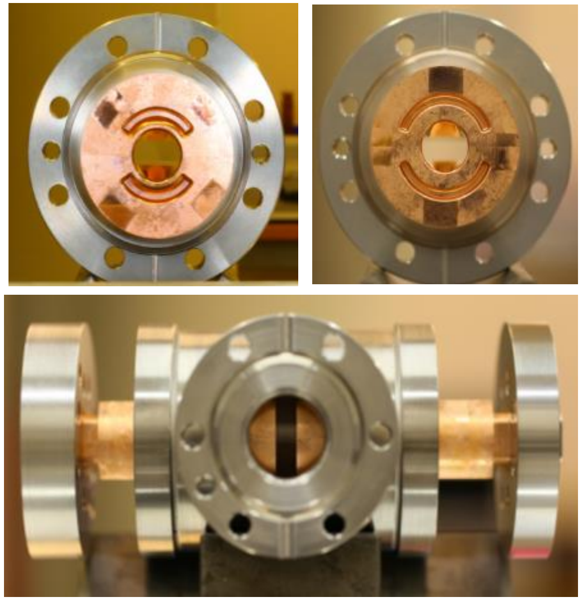


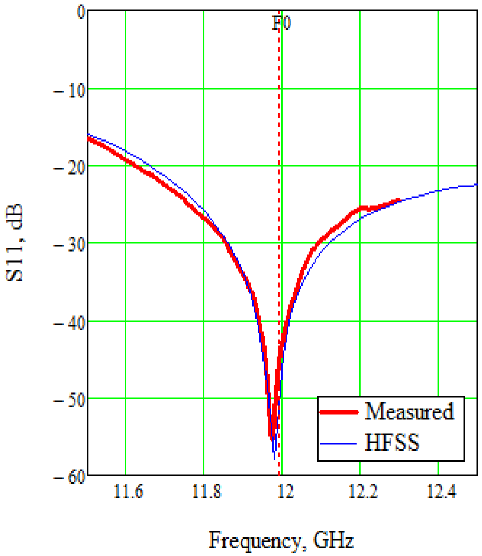


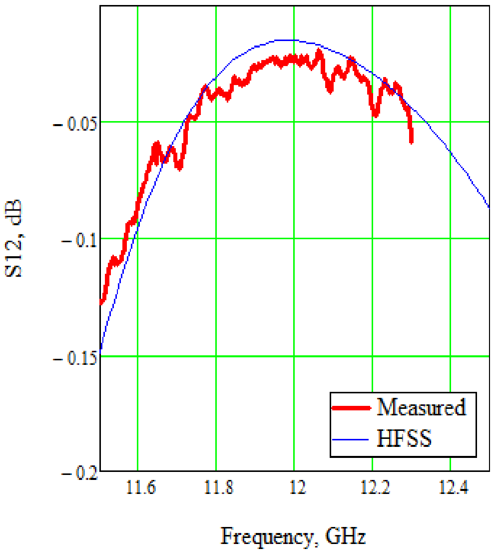
$E_{choke/max}$ (100 MW)=23.7 MV/m
($0.75 \times E_{max}$ in WR90)



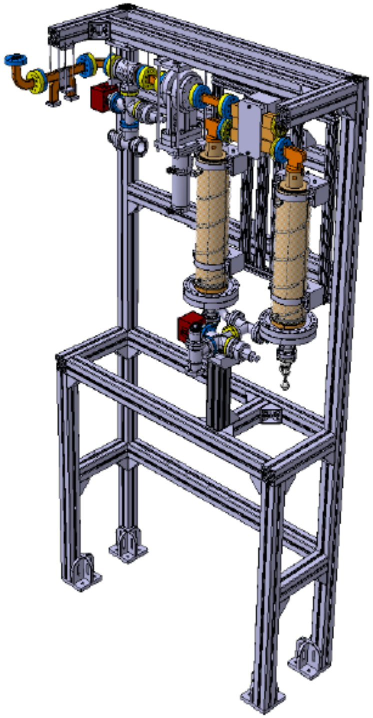
Slot width: 7mm

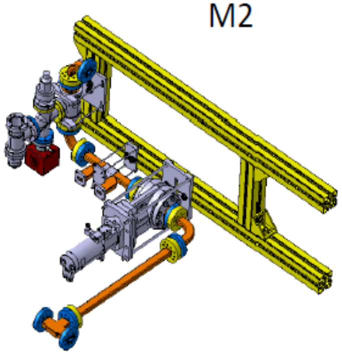


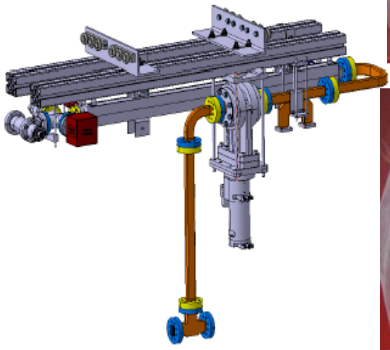


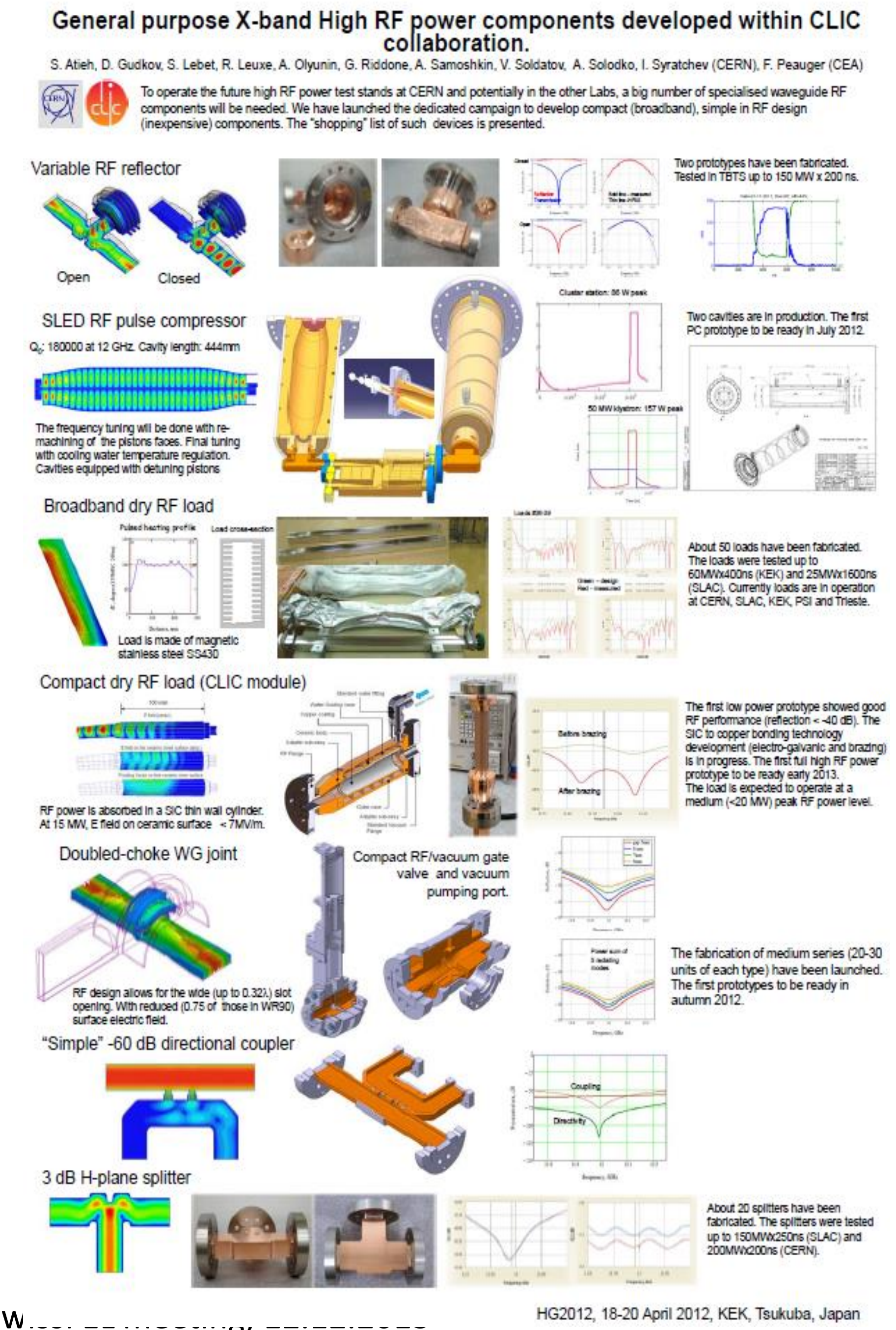


RF components & RF network integratio









General purpose X-band High RF power components developed within CLIC collaboration.

S. Atieh, D. Gudkov, S. Lebet, R. Leuxe, A. Olyunin, G. Riddone, A. Samoshkin, V. Soldatov, A. Solodko, I. Syratchev (CERN), F. Peauger (CEA)

To operate the future high RF power test stands at CERN and potentially in the other Labs, a big number of specialised waveguide RF components will be needed. We have launched the dedicated campaign to develop compact (broadband), simple in RF design (inexpensive) components. The "shopping" list of such devices is presented.

Variable RF reflector

Two prototypes have been fabricated. Tested in TBTS up to 150 MW x 200 ns.

SLED RF pulse compressor

Q_0: 180000 at 12 GHz. Cavity length: 444mm

The frequency tuning will be done with re-machining of the pistons faces. Final tuning with cooling water temperature regulation. Cavities equipped with detuning pistons

Two cavities are in production. The first PC prototype to be ready in July 2012.

Broadband dry RF load

Load is made of magnetic stainless steel SS430

About 50 loads have been fabricated. The loads were tested up to 60MWx400ns (KEK) and 25MWx1600ns (SLAC). Currently loads are in operation at CERN, SLAC, KEK, PSI and Trieste.

Compact dry RF load (CLIC module)

RF power is absorbed in a SiC thin wall cylinder. At 15 MW, E field on ceramic surface < 7MV/m.

The first low power prototype showed good RF performance (reflection < -40 dB). The SIC to copper bonding technology development (electro-galvanic and brazing) is in progress. The first full high RF power prototype to be ready early 2013. The load is expected to operate at a medium (<20 MW) peak RF power level.

Doubled-choke WG joint

RF design allows for the wide (up to 0.32λ) slot opening. With reduced (0.75 of those in WR90) surface electric field.

Compact RF/vacuum gate valve and vacuum pumping port.

The fabrication of medium series (20-30 units of each type) have been launched. The first prototypes to be ready in autumn 2012.

"Simple" -60 dB directional coupler

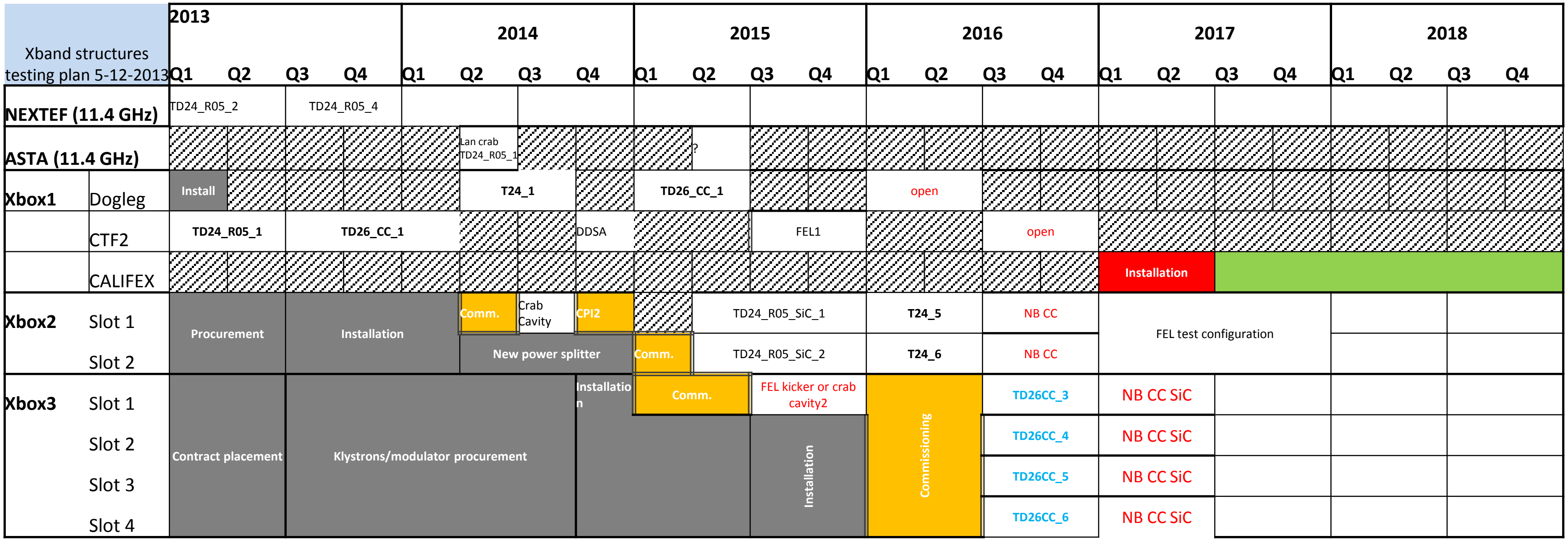
3 dB H-plane splitter

About 20 splitters have been fabricated. The splitters were tested up to 150MWx250ns (SLAC) and 200MWx200ns (CERN).

HG2012, 18-20 April 2012, KEK, Tsukuba, Japan

Since 2011, we have established special program for development of the new general purpose RF components.

Testing program

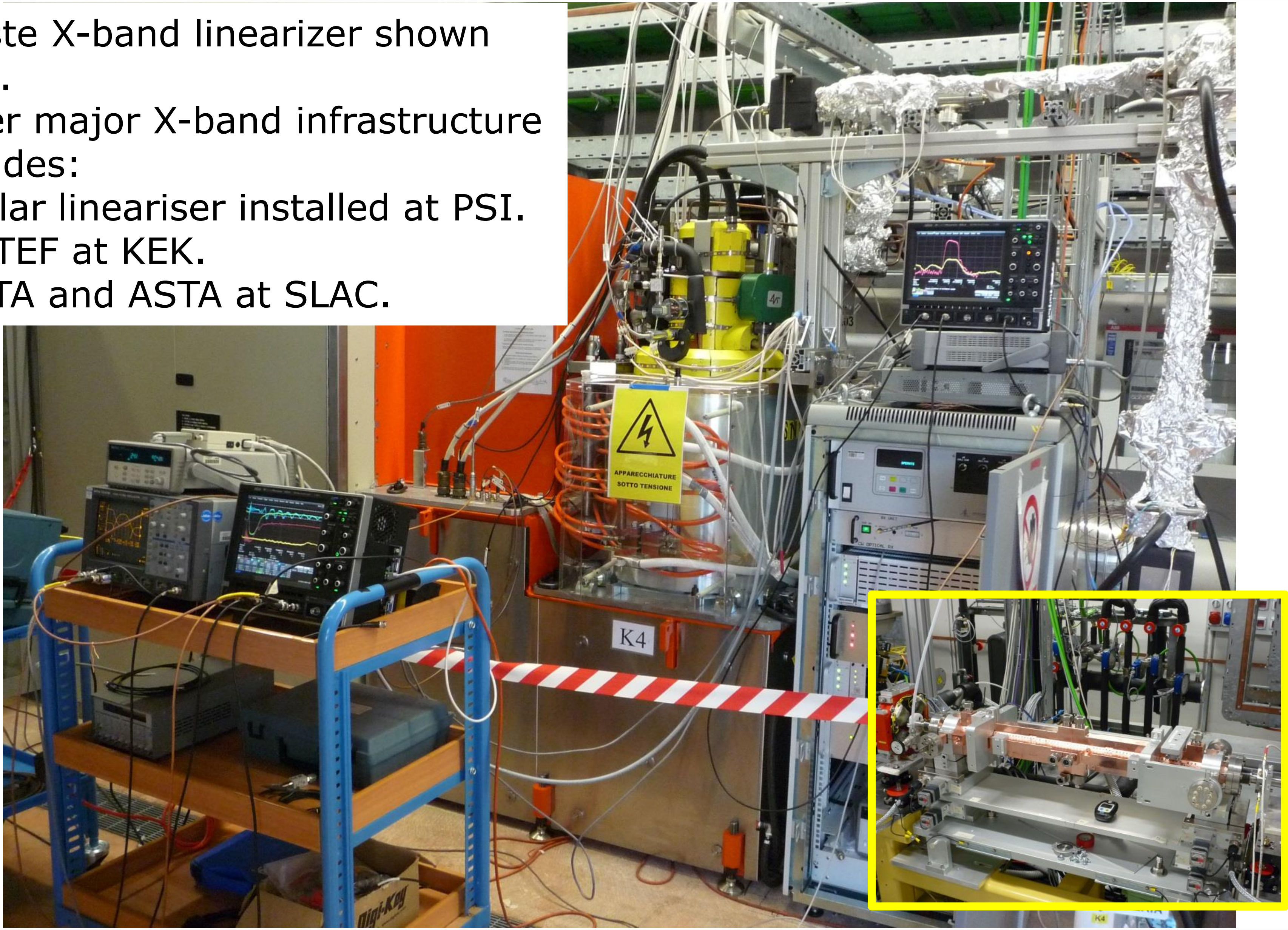


Xband structures testing plan 5-12-2013		2013				2014				2015				2016				2017				2018			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
NEXTEF (11.4 GHz)		TD24_R05_2		TD24_R05_4																					
ASTA (11.4 GHz)		▨	▨	▨	▨	▨	Lan crab TD24_R05_1	▨	▨	▨	?	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Xbox1	Dogleg	Install	▨	▨	▨	▨	T24_1		▨	TD26_CC_1		▨	▨	open		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	CTF2	TD24_R05_1		TD26_CC_1			▨	▨	DDSA	▨	▨	FEL1		▨	▨	open		▨	▨	▨	▨	▨	▨	▨	▨
	CALIFEX	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	Installation		🟩	🟩	🟩	🟩	🟩	🟩
Xbox2	Slot 1	Procurement		Installation			Comm.	Crab Cavity	CPI2	▨	TD24_R05_SiC_1			T24_5		NB CC		FEL test configuration							
	Slot 2						New power splitter			Comm.	TD24_R05_SiC_2			T24_6		NB CC									
Xbox3	Slot 1	Contract placement		Klystrons/modulator procurement					Installation	Comm.		FEL kicker or crab cavity2		Commissioning		TD26CC_3		NB CC SiC							
	Slot 2											Installation				TD26CC_4		NB CC SiC							
	Slot 3															TD26CC_5		NB CC SiC							
	Slot 4															TD26CC_6		NB CC SiC							

Increase in testing capability

X-band RF power plant

Trieste X-band linearizer shown here.
Other major X-band infrastructure includes:
Similar lineariser installed at PSI.
NEXTEF at KEK.
NLCTA and ASTA at SLAC.



The main trends

$P_{peak} \propto G^2$ for a fixed geometry

$P_{peak} \propto f^{-1/2}$ for a fixed geometry and fixed energy gain

$\frac{R}{Q} \propto const$ (per cell) $Q \propto f^{-1/2}$

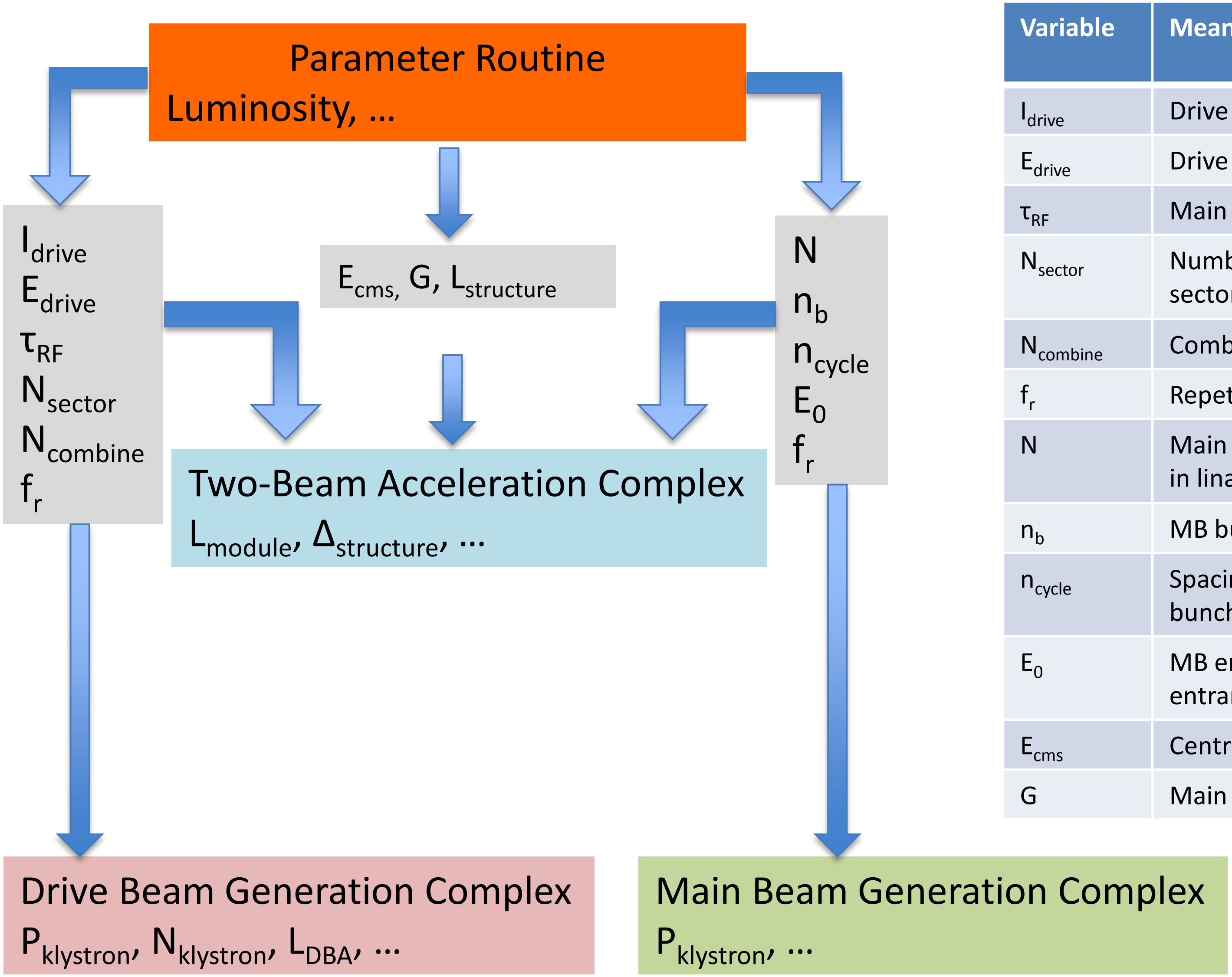
$\tau_{fill} \propto f^{-3/2}$ for constant αl where $\alpha = \frac{\omega}{2Qv_g}$

But

$a \propto f^{-1}$ Physical aperture

$\frac{R}{Q}(a)$ You need a computer…

CLIC optimization loops



Parameter Routine
Luminosity, …

I_{drive}
E_{drive}
τ_{RF}
N_{sector}
$N_{combine}$
f_r

E_{cms}, G, $L_{structure}$

N
n_b
n_{cycle}
E_0
f_r

Two-Beam Acceleration Complex
L_{module}, $\Delta_{structure}$, …

Drive Beam Generation Complex
$P_{klystron}$, $N_{klystron}$, L_{DBA}, …

Main Beam Generation Complex
$P_{klystron}$, …

Variable	Meaning	Current value
I_{drive}	Drive beam current	101A
E_{drive}	Drive beam energy	2.37GeV
τ_{RF}	Main linac RF pulse length	244ns
N_{sector}	Number of drive beam sectors per linac	4
$N_{combine}$	Combination number	24
f_r	Repetition rate	50Hz
N	Main beam bunch charge in linac	3.72e9
n_b	MB bunches per pulse	312
n_{cycle}	Spacing between MB bunches	6 cycles
E_0	MB energy at linac entrance	9GeV
E_{cms}	Centre-of-mass energy	500GeV
G	Main linac gradient	100MV/m

RF structure database

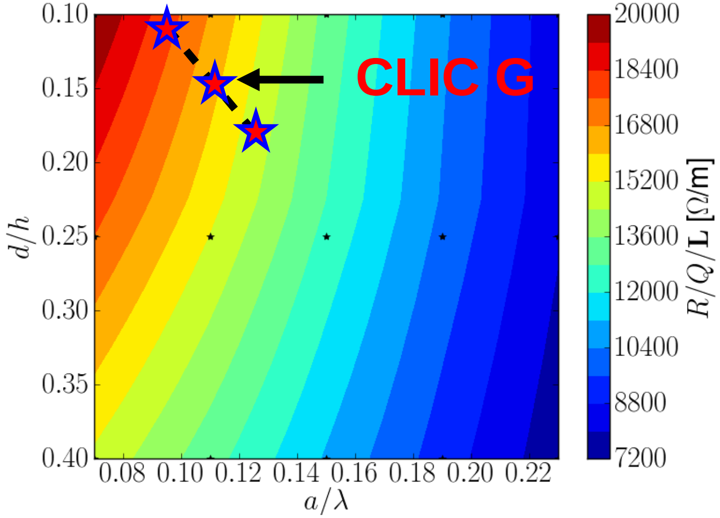
K. Sjobak

Determines the properties and performance of an rf structure as a function of length and aperture and iris thickness profiles.

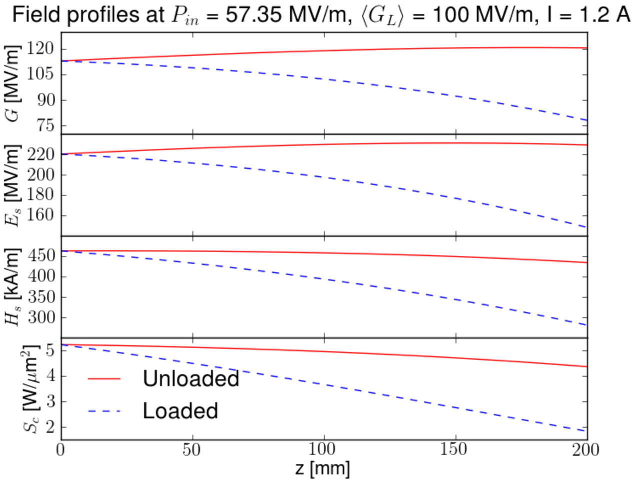
Utilizes breakdown scaling laws and database of pre-optimized cells.

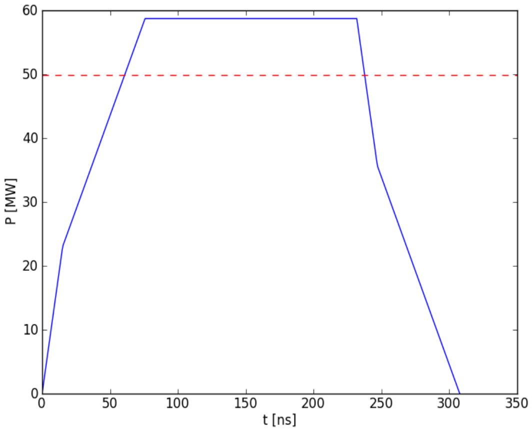
Contains *Q*, *R/Q*, v_g, E_s, S_c, H_s, W_a, W_Q, W_f

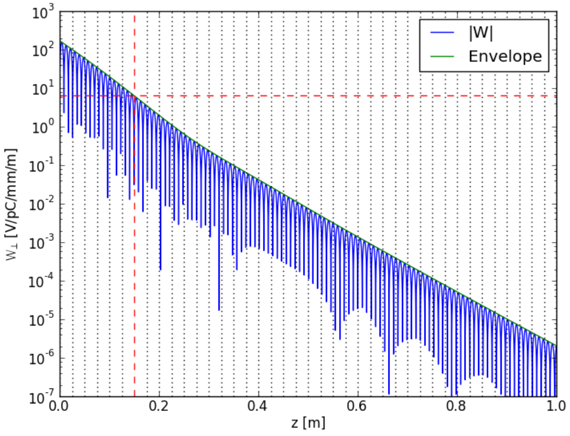
- Fundamental mode properties
- High-gradient performance
- Transverse wakefield suppression



Example - Single cell data for *R/Q(a,*







Field profiles

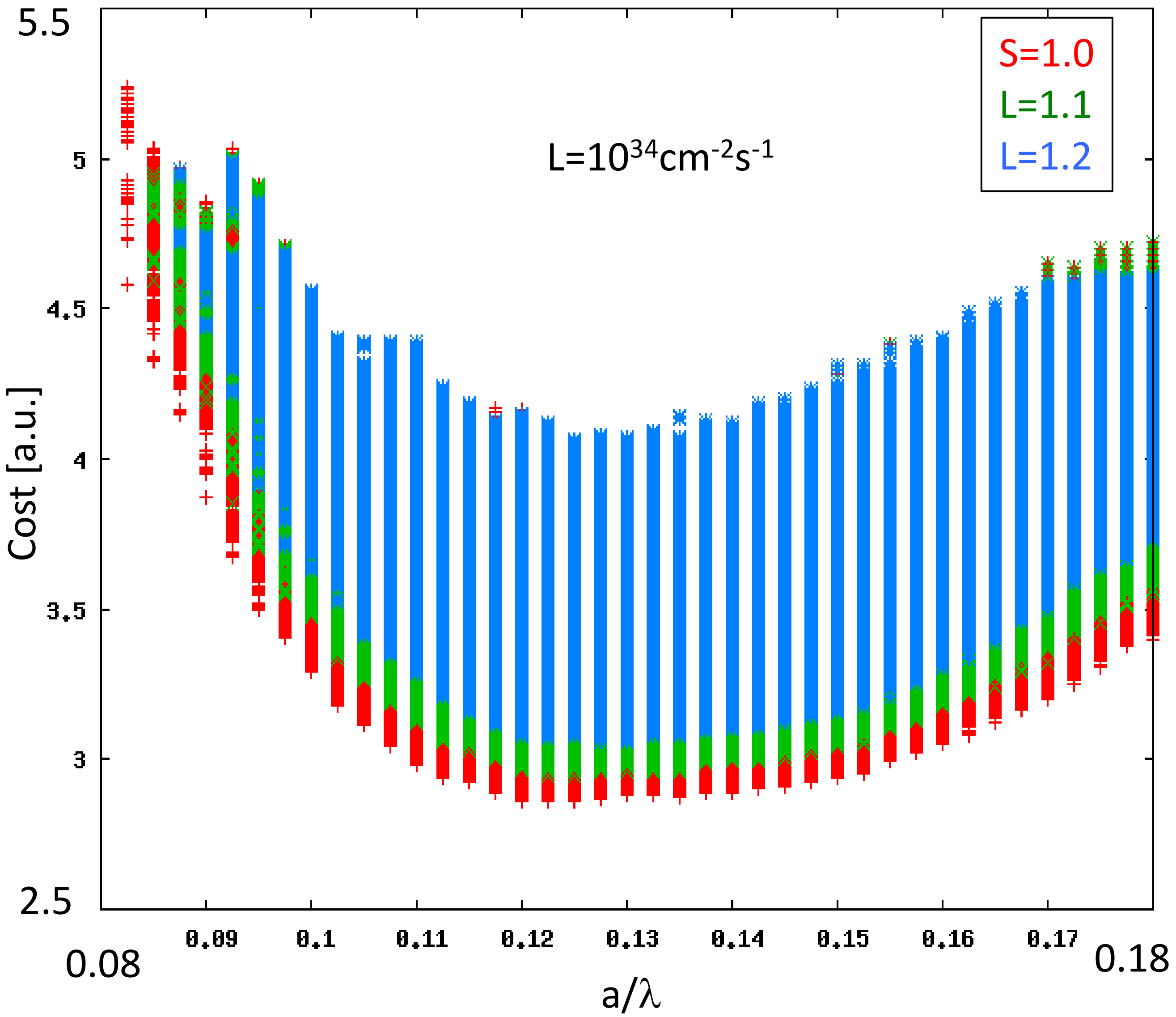
Pulse shape

Transverse wakefield

Impact of RF Constraints

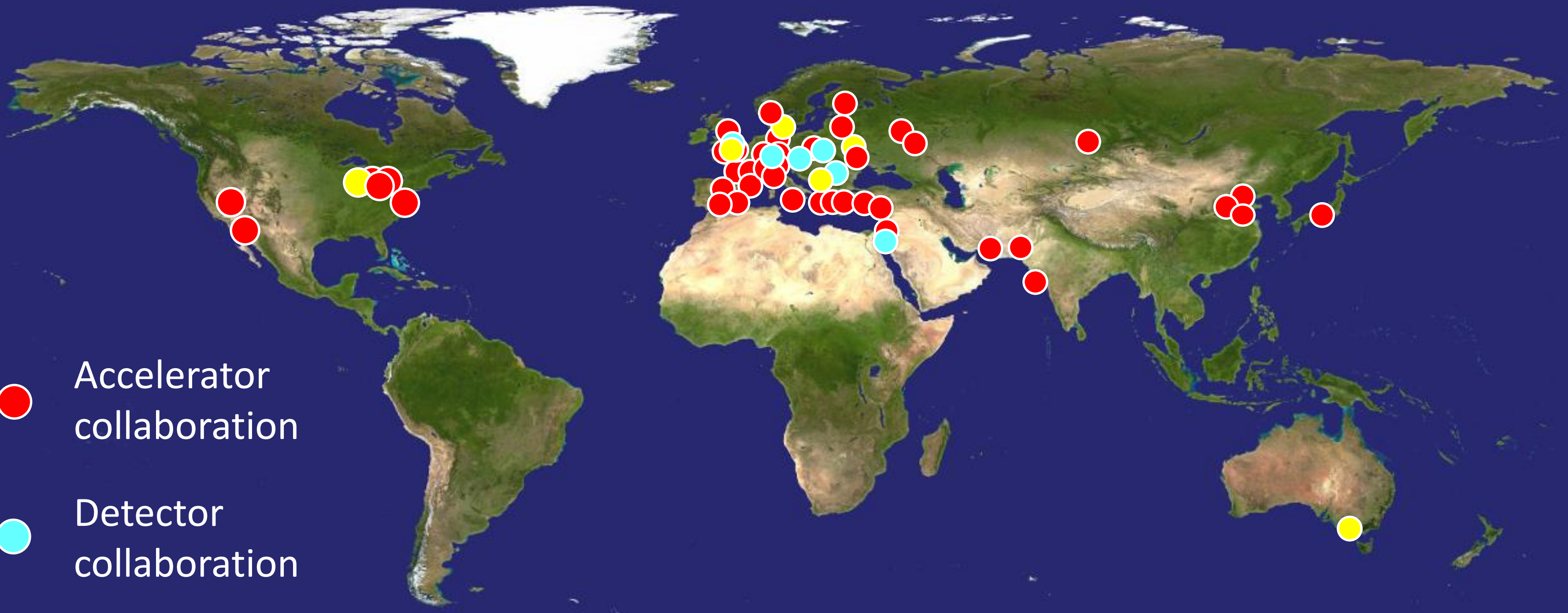
Safety factor S:
Structure can tolerate S-times the nominal gradient for the full pulse length

10% gradient margin costs 0.1 a.u.



CLIC Collaboration

29 Countries – over 70 Institutes



🔴 Accelerator collaboration

🔵 Detector collaboration

🟡 Accelerator + Detector collaboration

New Directions

The kind of **projects** we have identified which potentially benefit from high-gradient technology include:

- FELs
- Compton sources
- Medical linacs
- Imaging scanners
- Pulsed neutron sources

There are also **components** such as:

- Phase linearizing cavities
- Deflectors
- Rf guns

Today we will consolidating and expand this list!