Status report from the CLIC Test Facility 3 Two-Beam Test Stand

US High Gradient Research Collaboration Workshop 2011, SLAC, CA, USA

Erik Adli, University of Oslo, Norway

For the CLIC/CTF3 collaboration

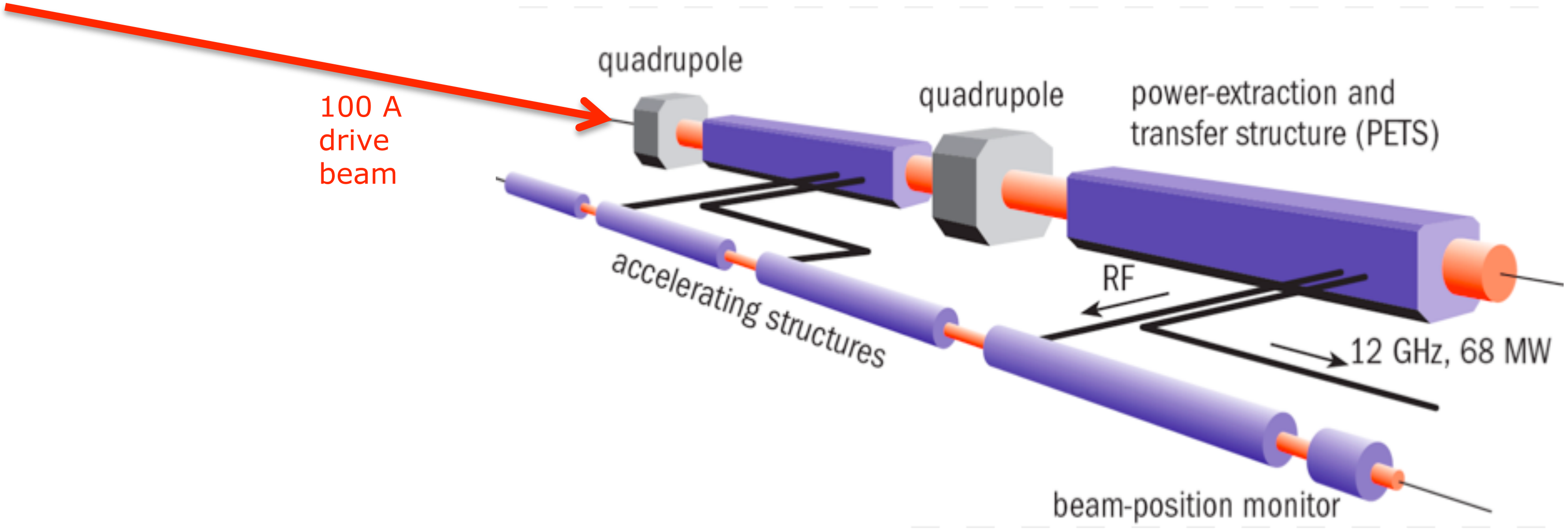
February 9, 2011

OUTLINE

- Introduction to CTF3 and TBTS
- TBTS structures
- Main results
- Details on how we achieved these results
- Future plans for CLIC Two-Beam Acceleration
- Conclusions

The Compact Linear Collider (CLIC)

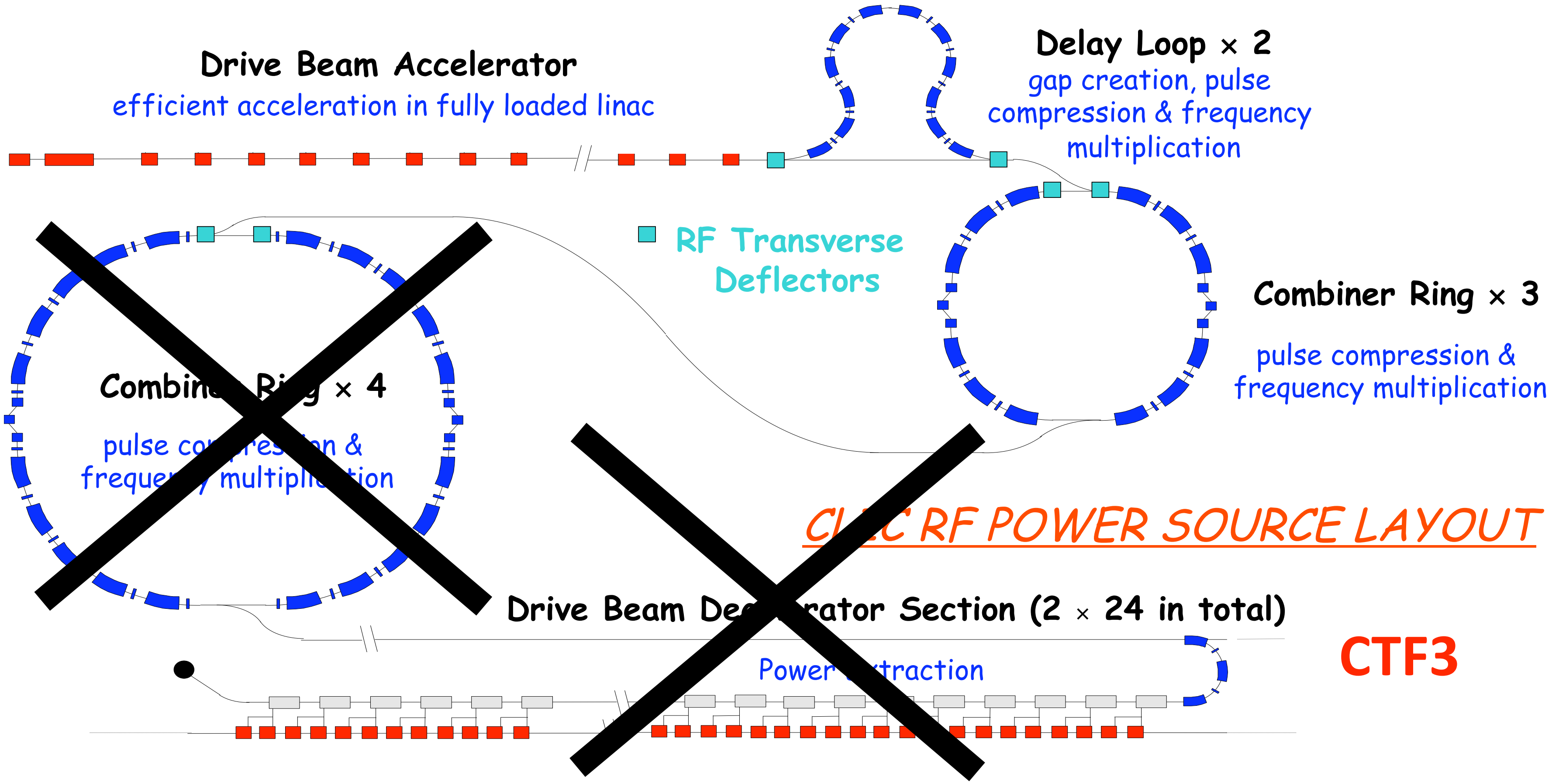
- The Compact Linear Collider (CLIC): study for a Multi-TeV linear collider, with design parameters of 3 TeV COM and luminosity of 2 x 10^{34} $cm^{-2}s^{-1}$
- Main linac uses normal-conducting accelerating structures with an accelerating gradient of **100 MV/m** (loaded)
- The large number of structures leads to a small rf break down rate criterion (10^{-7} per structure per pulse), and the charge required to reach the luminosity goals must be distributed within **short rf pulses** (240 ns)
- **CLIC two-beam acceleration scheme**: high-power short rf pulses for main linacs are extracted from a compressed high-intensity 100 A e^- **drive beam.** Allows for **good machine efficiency.**



CLIC two-beam acceleration scheme

New collaboration web-side: http://clic-study.org/

CLIC drive beam scheme versus CLIC Test Facility 3



Drive Beam Accelerator

efficient acceleration in fully loaded linac

Delay Loop × 2

gap creation, pulse compression & frequency multiplication

RF Transverse Deflectors

Combiner Ring × 3

pulse compression & frequency multiplication

Combiner Ring × 4

pulse compression & frequency multiplication

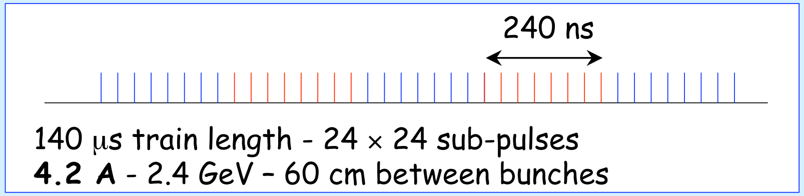
CLIC RF POWER SOURCE LAYOUT

Drive Beam Decelerator Section (2 × 24 in total)

Power Extraction

CTF3

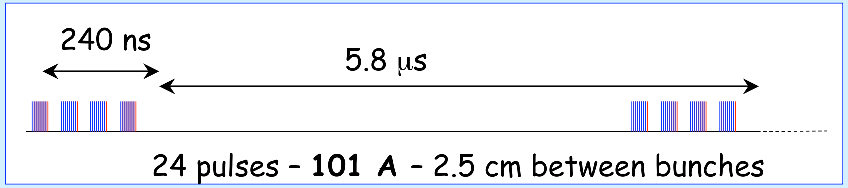
Drive beam time structure - initial



140 μs train length - 24 × 24 sub-pulses

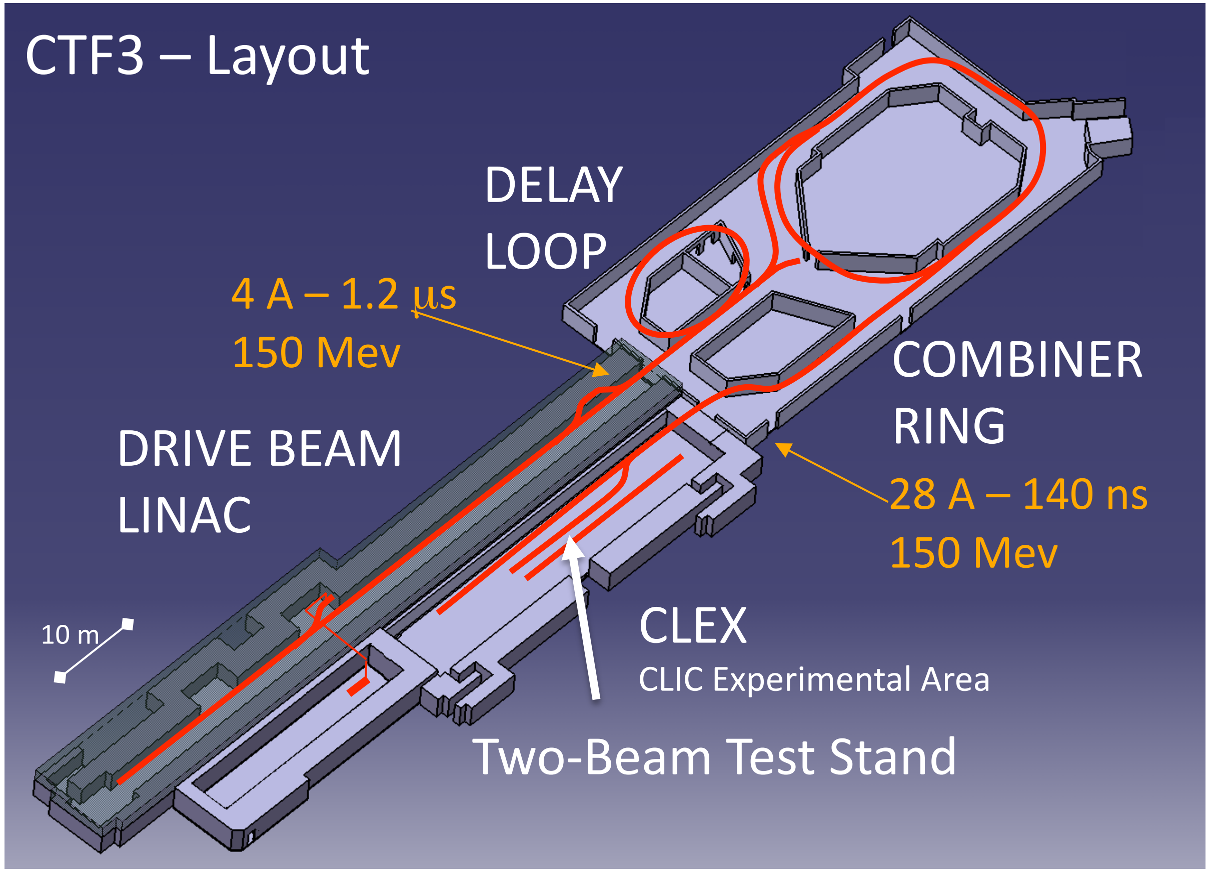
4.2 A - 2.4 GeV – 60 cm between bunches

Drive beam time structure - final



24 pulses – **101 A** – 2.5 cm between bunches

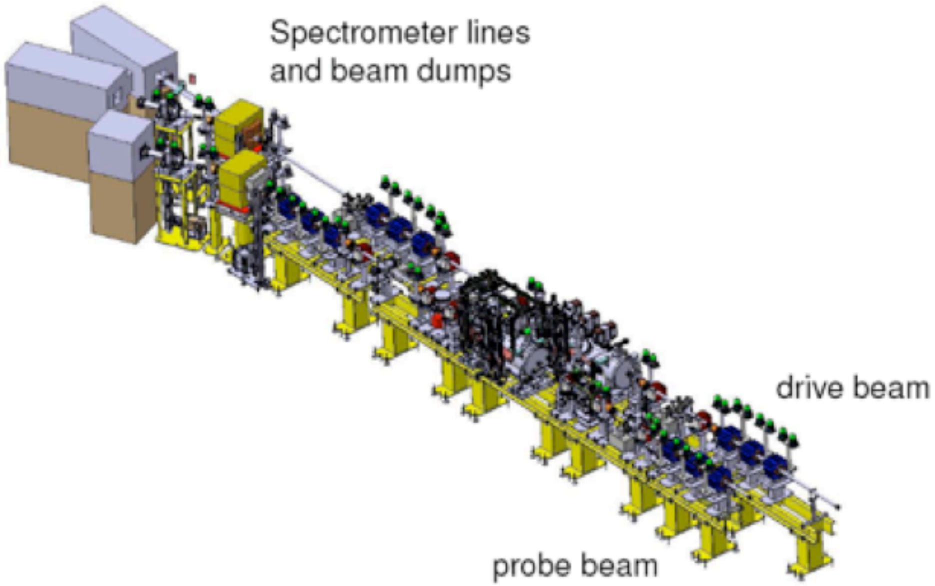
CLIC Test Facility 3 (CTF3) at CERN



CLIC Test Facility 3 : designed to test key concept of the CLIC two-beam scheme. Main parts :

- **Drive Beam generation**: acceleration in a fully loaded linac with > 95 % efficiency and bunch frequency multiplication by a factor x 2 x 4 (from 1.5 GHz to 12 GHz)
- **Two-Beam Acceleration experiment (described in this talk)**
- Deceleration experiment, TBL (not described here)
- Instrumentation tests (not described here)

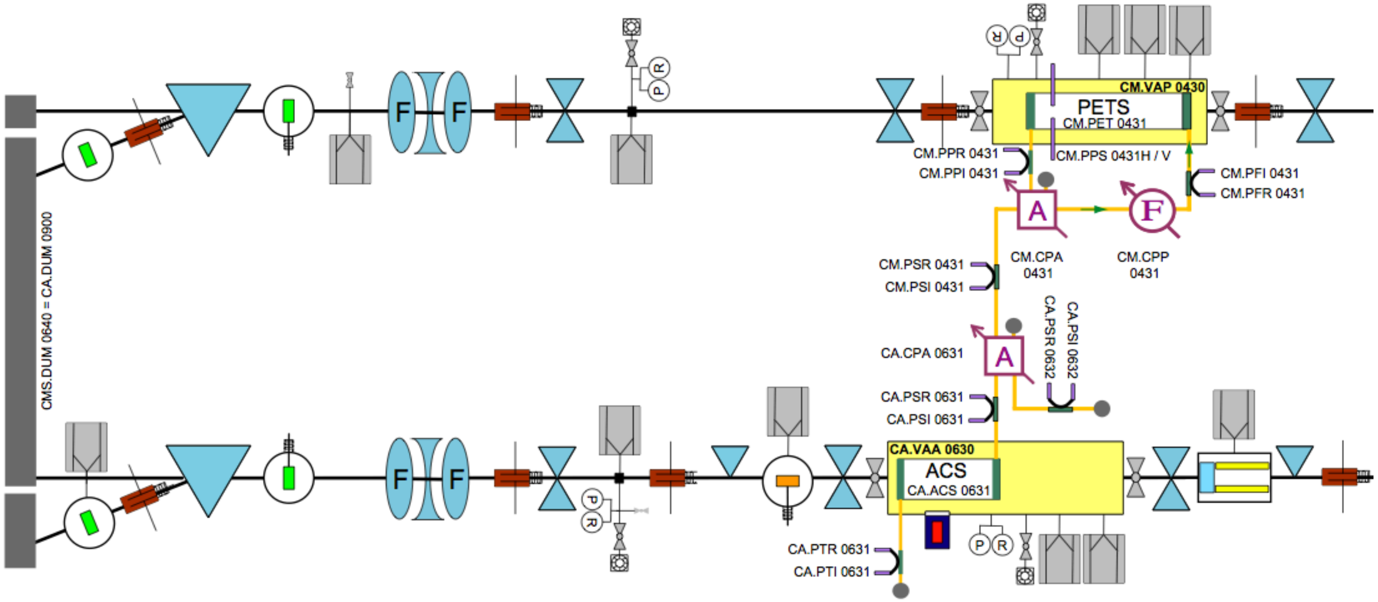
Two-Beam Test Stand (TBTS)



TBTS = two beams + structures + instrumentation

Subjects of study include :

1. acceleration and deceleration
2. effect of higher order modes, study of transverse kicks and wake field monitors
3. Rf breakdown studies, in the presence of beam
4. timing of the two beams
5. full system behavior; from component prototypes to two-beam acceleration unit prototype; Cross talk between drive and probe beam



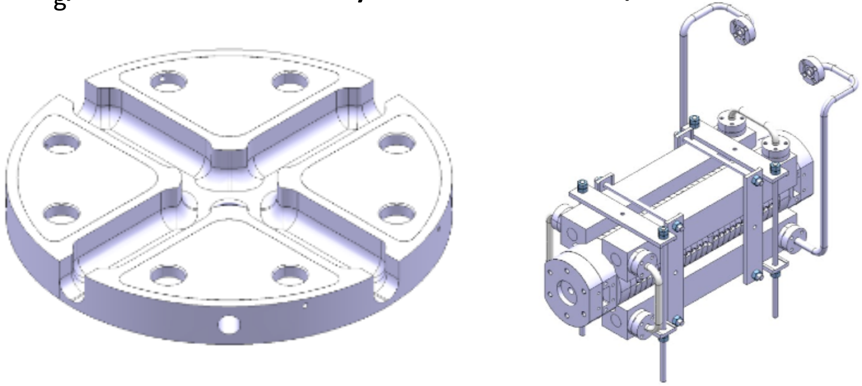
Drive Beam (up to 28A, 150 MeV, 12 GHz, 140 ns @ 12 GHz)

Probe Beam (up to 1A, 180 MeV, 1.5 GHz, 150 ns)

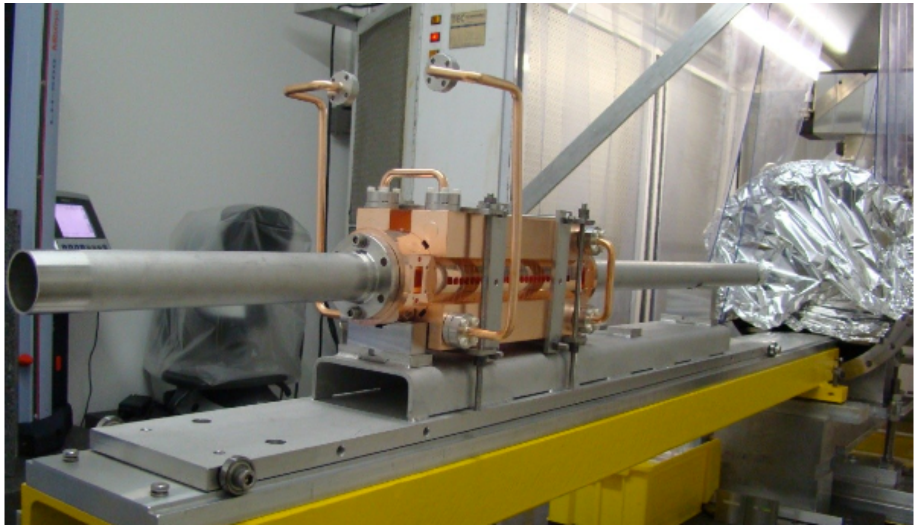
R. Ruber, Uppsala University

TBTS accelerating structure: TD24

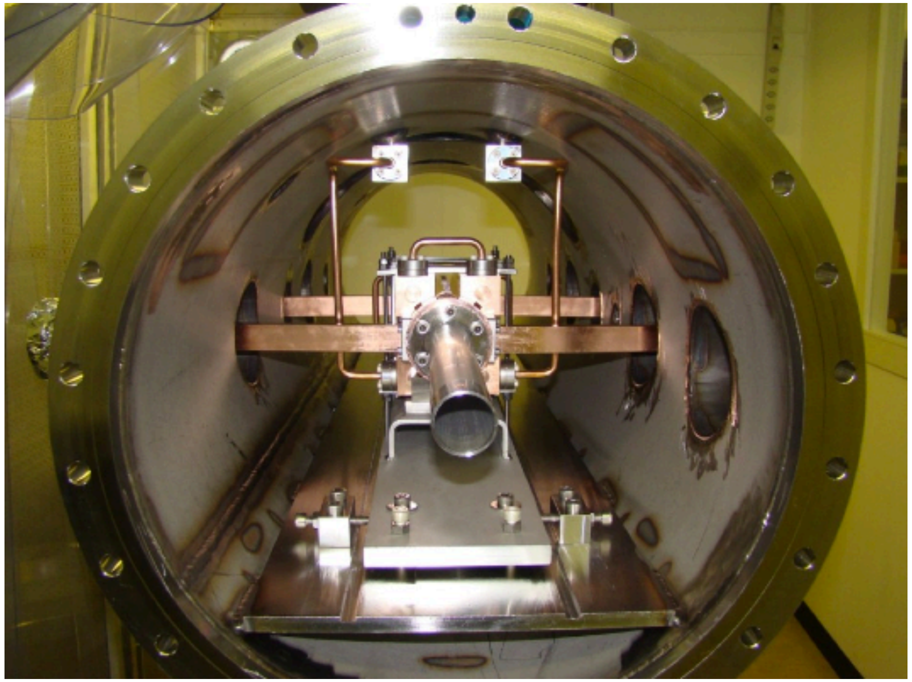
TD24: Tapered, wave-guide damped 24 cell structure with $v_g/c = 1.8$. 40 MW yields ~ 100 MV/m.



Bonded at 1000 deg (design for brazed)



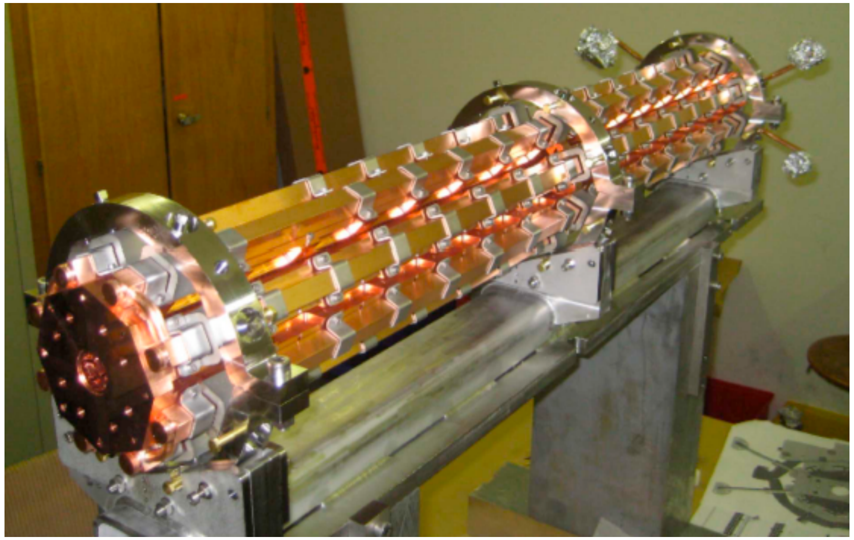
	120°/cell		comments
f [GHz]	11.995		
S12	0.6542		
t_f [ns]	64.55		
Q^{Cu}	5732		
Gradient averaged over all cells			
V_{26} [V]@P_{in} = 1 W	3340		2 matching +24 regular cells L_{acc} = 227.7 mm,
G_{26} [V/m]@P_{in} = 1 W	14661		
P_{in} [MW]@<G_{26}=100MV/m>	46.5		
Gradient averaged over regular cells only			
V_{24} [V]@P_{in} = 1 W	3078		24 regular cells only L_{acc} = 200.0 mm,
G_{24} [V/m]@P_{in} = 1 W	15390		
P_{in} [MW]@<G_{24}=100MV/m>	42.2		



A. Grudiev, RF design and parameters of 12 GHz TD24_vg1.8_disk

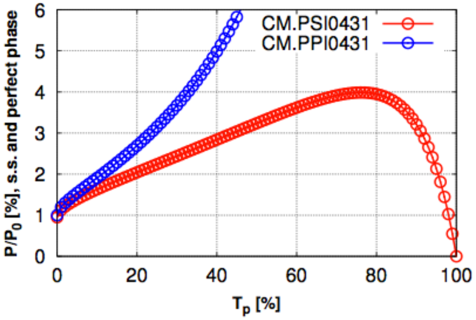
https://edms.cern.ch/document/1070498/1

TBTS power extraction structure (PETS)

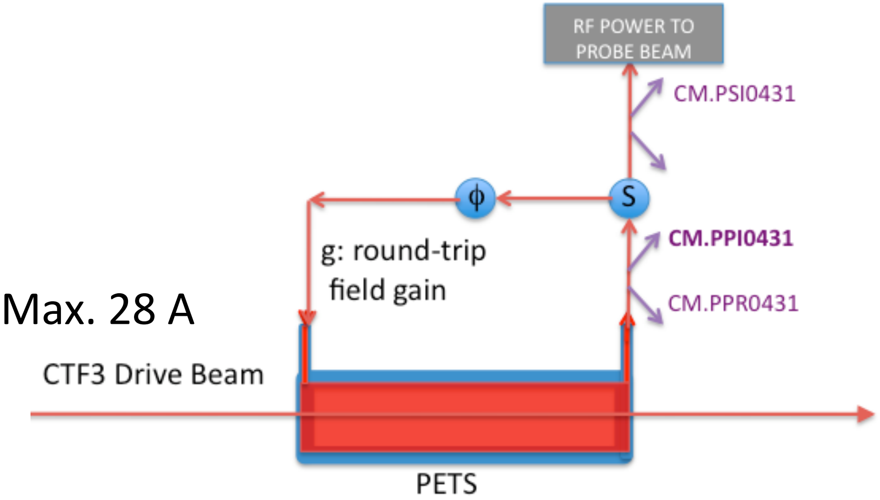


CLIC 12 GHz PETS prototype

TBTS PETS has CLIC-design where a 0.23 m PETS with 100A gives 135 MW power. TBTS x4 longer (1m) to compensate for x4 lower CTF3 drive beam current. In addition, field recirculation (resonant loop) is added for increased power production :

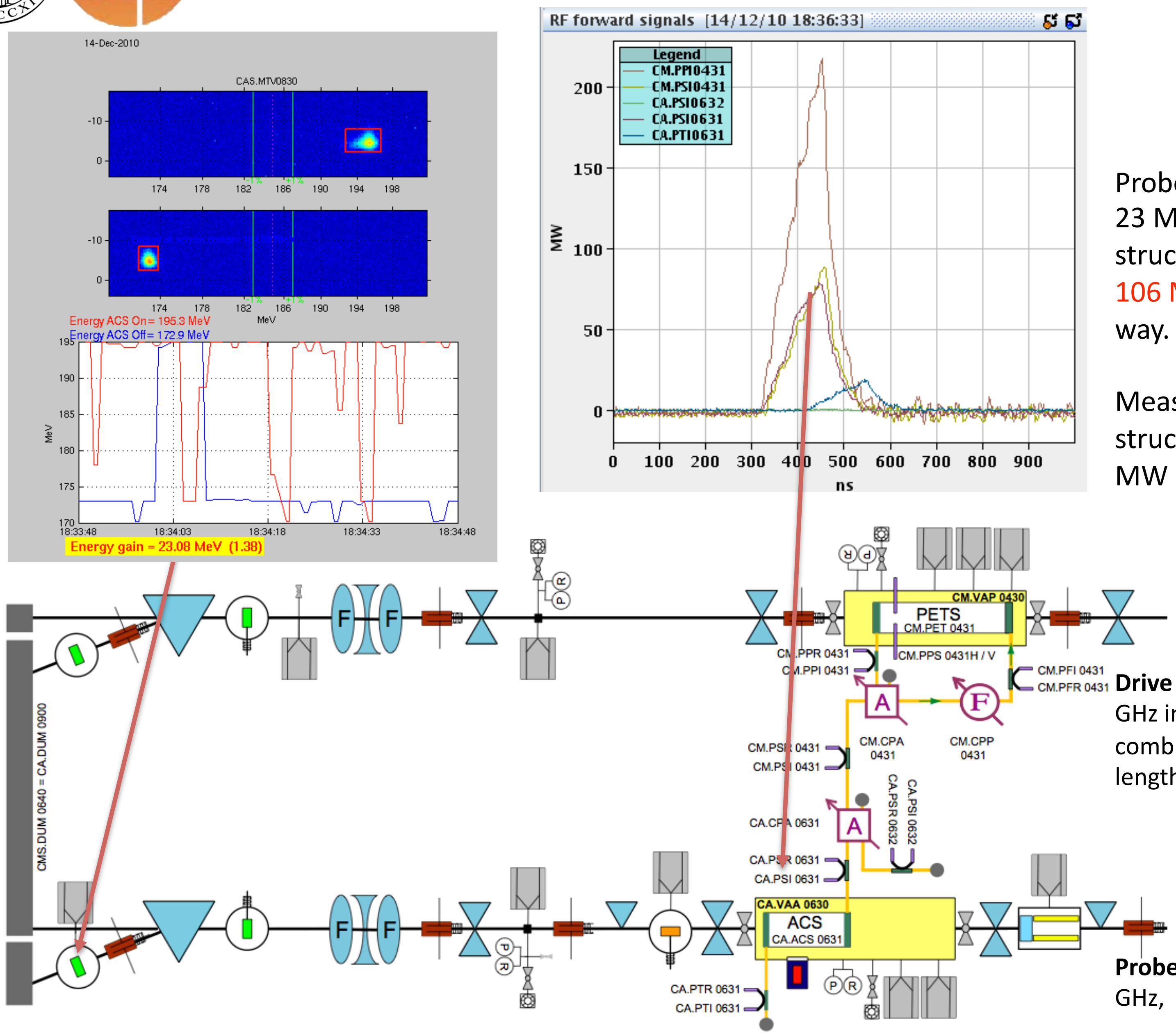


Loop allows for x4 more power to the structure.



TBTS PETS tank with power splitter and phase shifter

2010: Two-beam acceleration with a gradient of 106 MV/m



December 14, 2010:

Probe beam accelerated by 23 MV in a TD24 accelerating structure, corresponding to 106 MV/m, in a reproducible way.

Meas. PETS power input to structure ~ 80 MW (~200 MW in the resonant loop)

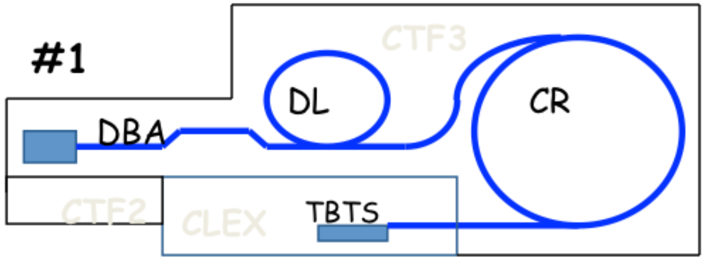
Drive beam: 12.5 A, 113 MV, 12 GHz in CLEX (1.5 GHz beam combined factor 8), 140 ns pulse length

Probe beam: 0.08 A, 173 MV, 1.5 GHz, 8 ns pulse length

Progress in drive beam generation

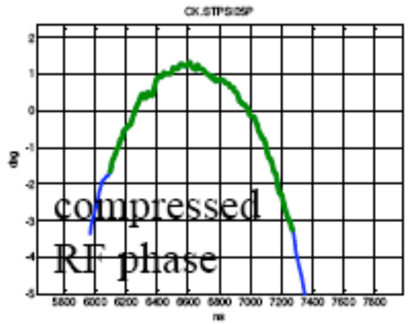
Drive Beam Optimization for RF power production

- Bunch length
- Combination phase
- Phase variation along the pulse
- All affecting power production efficiency (form factor F)

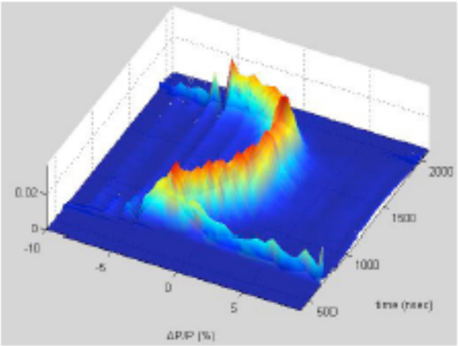


Example: bunch phase errors due to LIPS pulse compressors in linac .

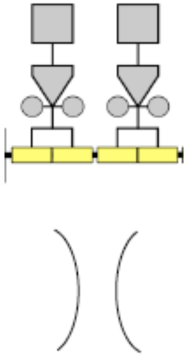
Needs careful tuning (and in 2010 we had new operation point (E, I) due to missing klystron.



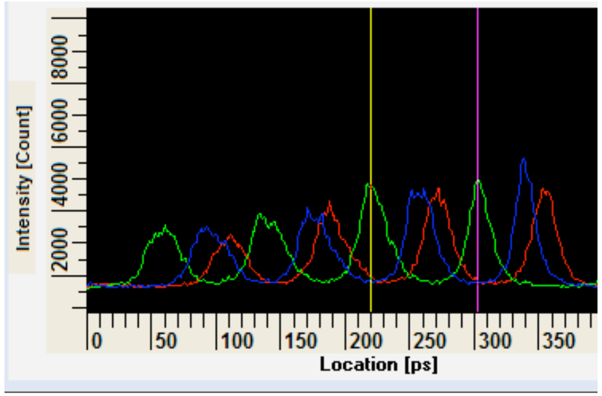
Rf phase

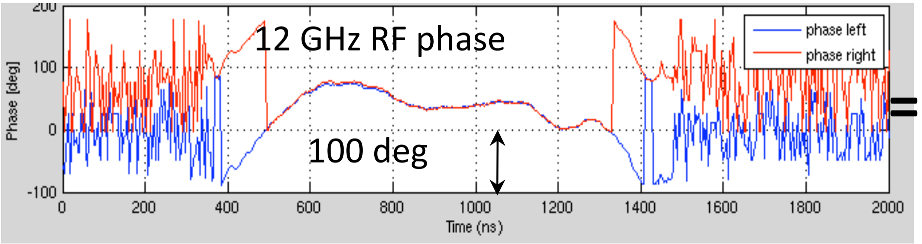


example linac energy profile



compensation





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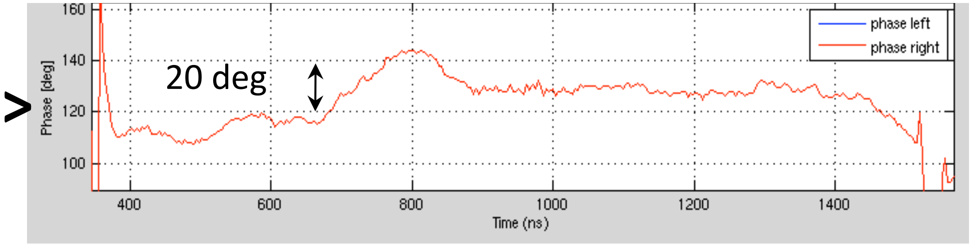


Example before optimization: ~20% reduction in power due to combination dephasing

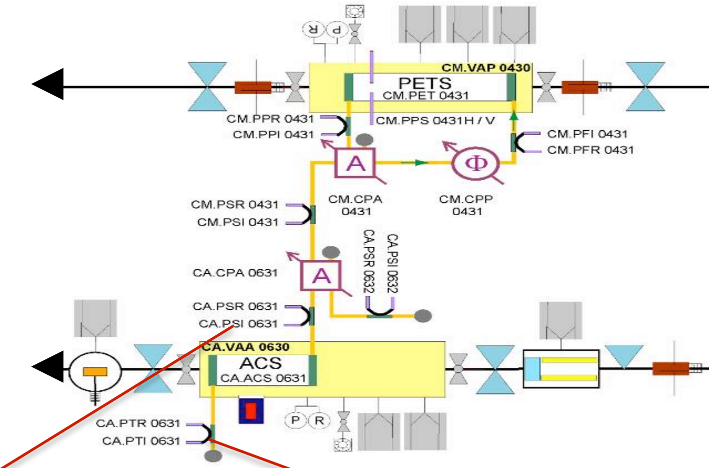
After optimization:~ 1% reduction

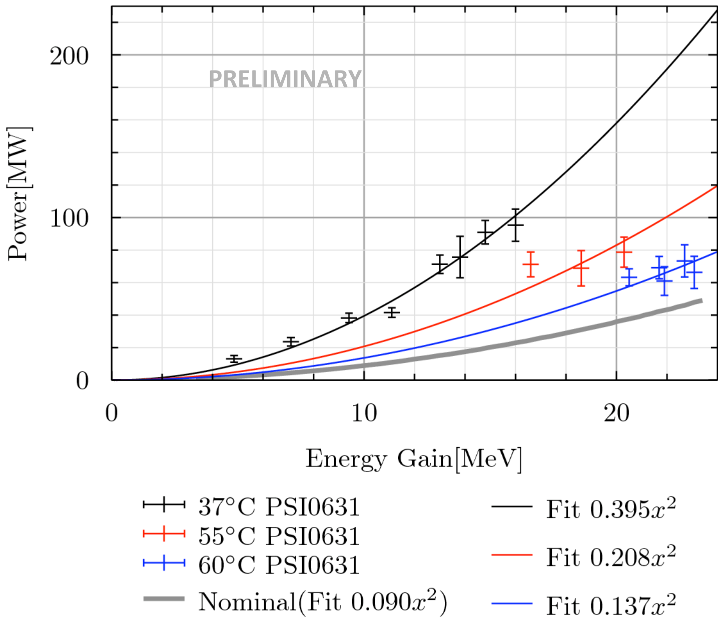
Erik Adli, Reidar Lillestøl, Sep 2010

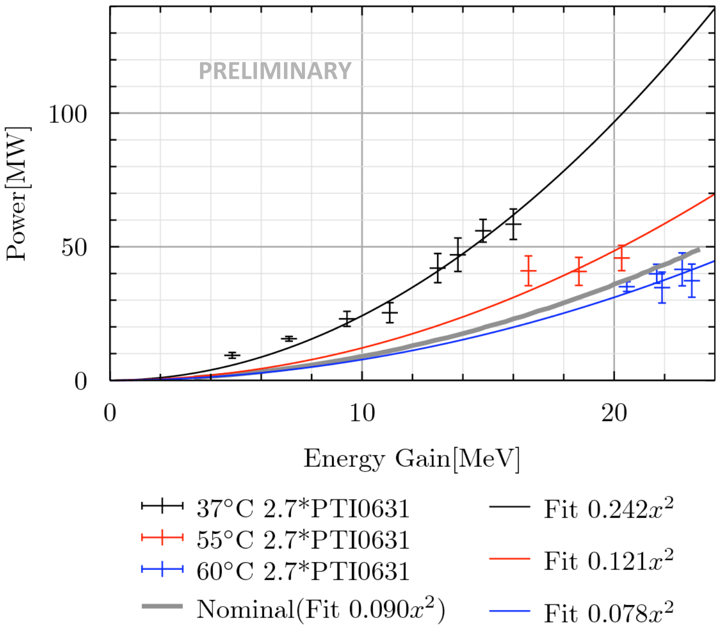
Difficulties reaching nominal gradient, Fall 2010

Javier Barranco

First two-beam accelerations attempts (black curves) : **noticed factors up to x 3-4 more power than estimated for a given measured acceleration!** Part of the problem was calibration issues (~ 100 dB attenuation, in couplers, cables, fixed and variable attenuators). **But we could not reach CLIC gradient with available input power,** (even with recirculation, for a long time.



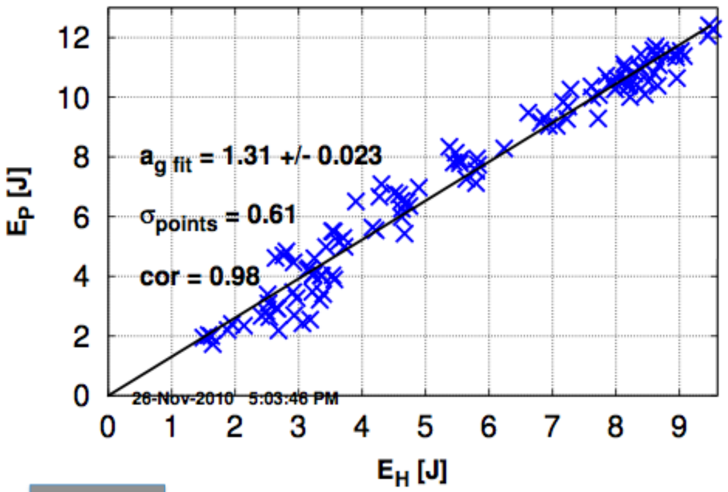

Power measured at structure input


Power measured at structure output, renormalized using known attenuation

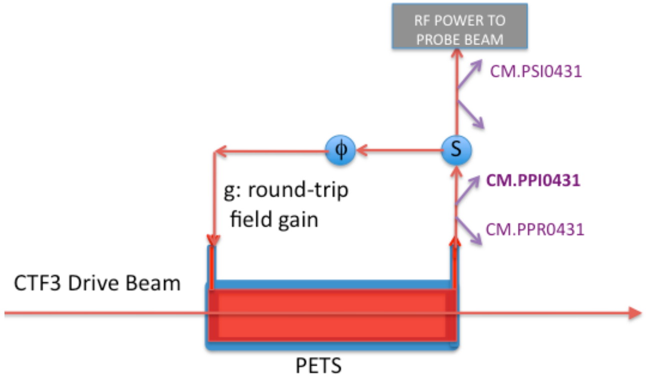
Progress in PETS rf power production characterization

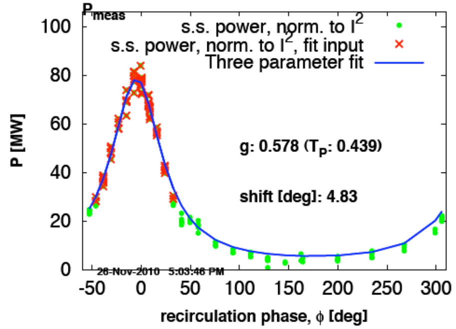
$$E_P = \int \mathrm{d}t\{P_{\mathrm{out}} + P_{\mathrm{lost}}\}$$

$$E_H = \int \mathrm{d}t UI$$

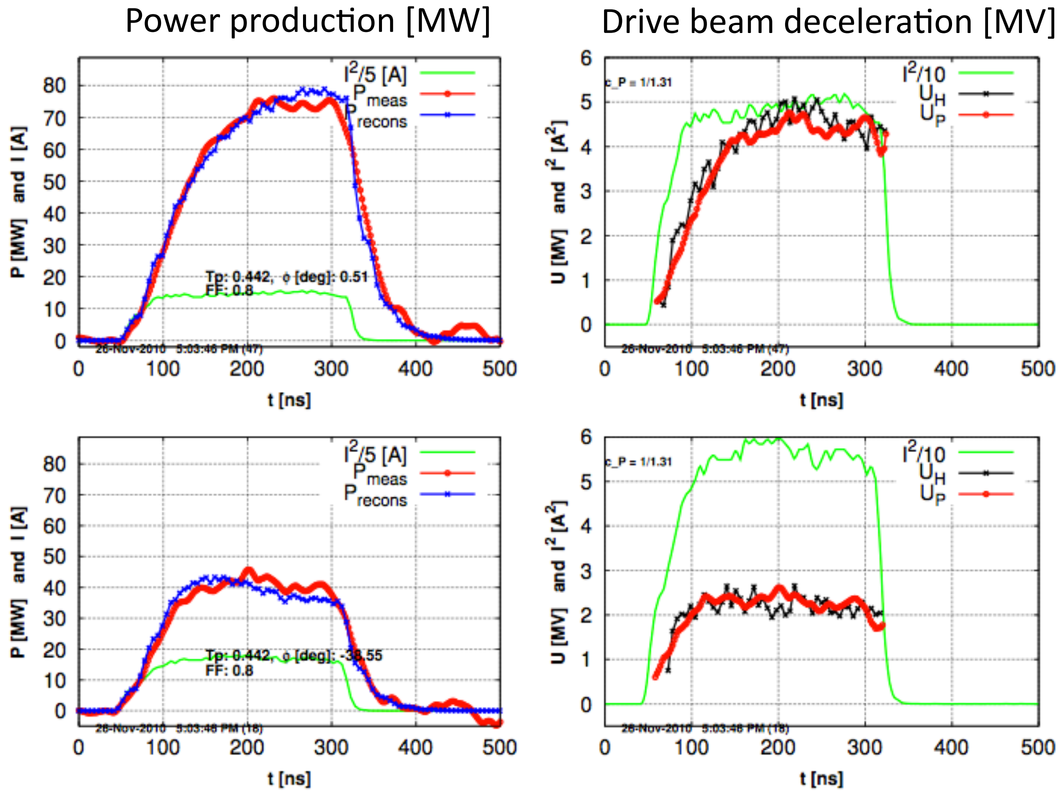


Correlated deceleration and power measurements, applying a simple two-parameter model of PETS with recirculation (g, ϕ).
Shows good reconstruction, and help identify calibration issues (here: 1 dB out of 100 dB attenuation)





Model ident. with phase scans.

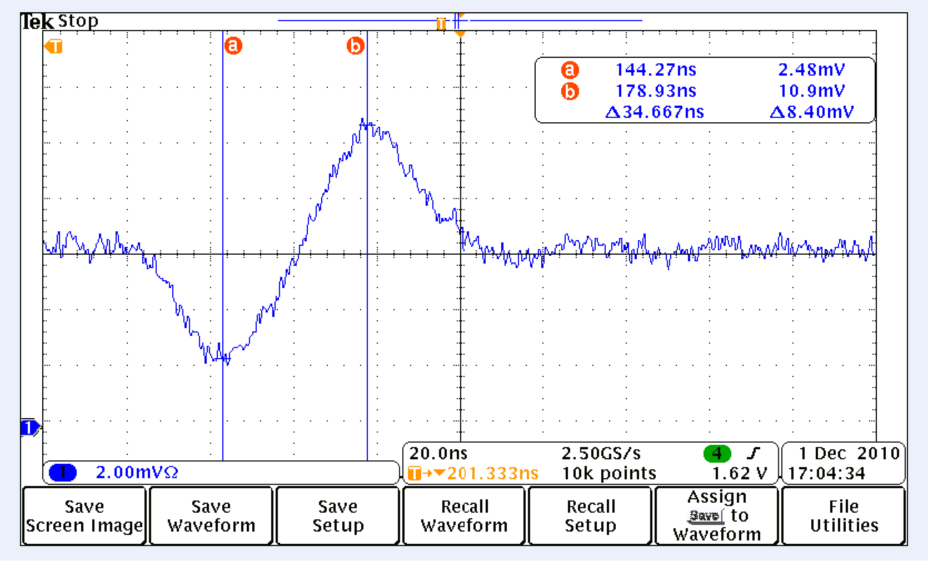

Power production [MW]

Drive beam deceleration [MV]

Measurement of resonant frequency of TD24

”Pinging” structure with short probe beam (10 ns << t_{fill}), mixing with known signal and checking difference signal:

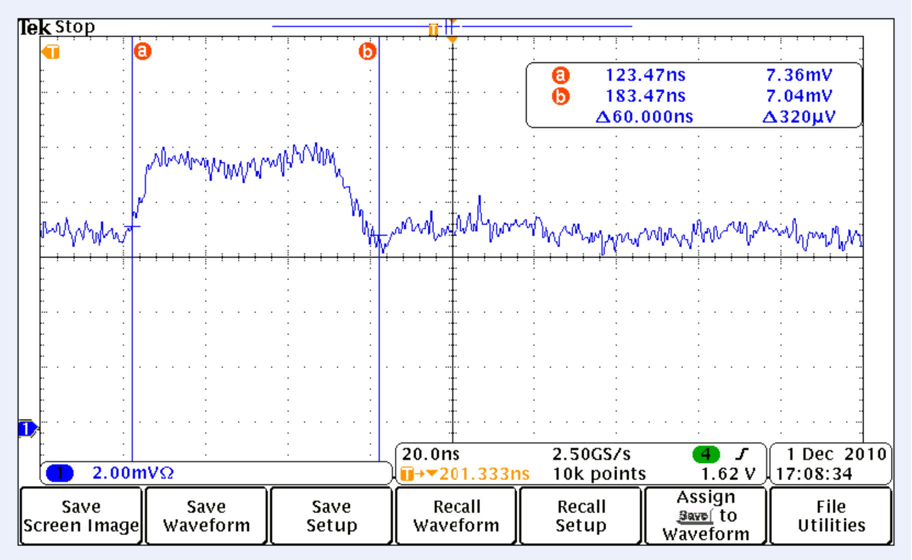
Mixing with signal of 11.994 MHz



a 144.27ns 2.48mV
b 178.93ns 10.9mV
Δ34.667ns Δ8.40mV

1 2.00mVΩ
20.0ns 2.50GS/s
T→▼201.333ns 10k points
4 ƒ 1.62 V
1 Dec 2010
17:04:34

Mixing with signal of 12.009 MHz



a 123.47ns 7.36mV
b 183.47ns 7.04mV
Δ60.000ns Δ320µV

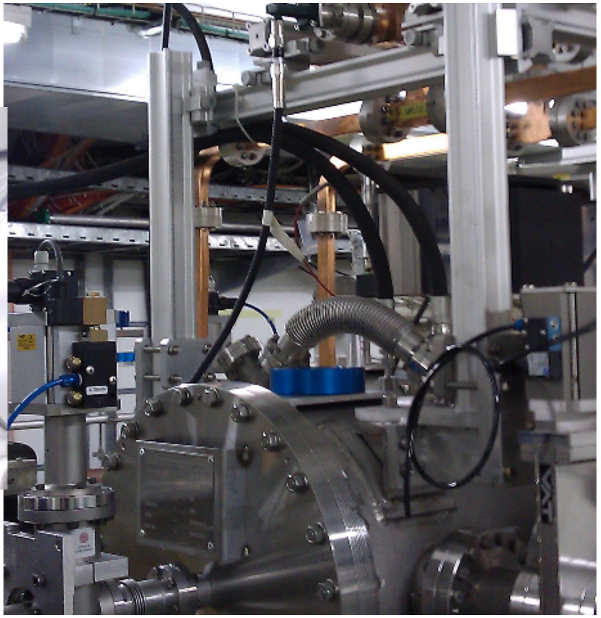
1 2.00mVΩ
20.0ns 2.50GS/s
T→▼201.333ns 10k points
4 ƒ 1.62 V
1 Dec 2010
17:08:34

Measurements indicated that resonant frequency was 10-15 MHz higher than nominal.

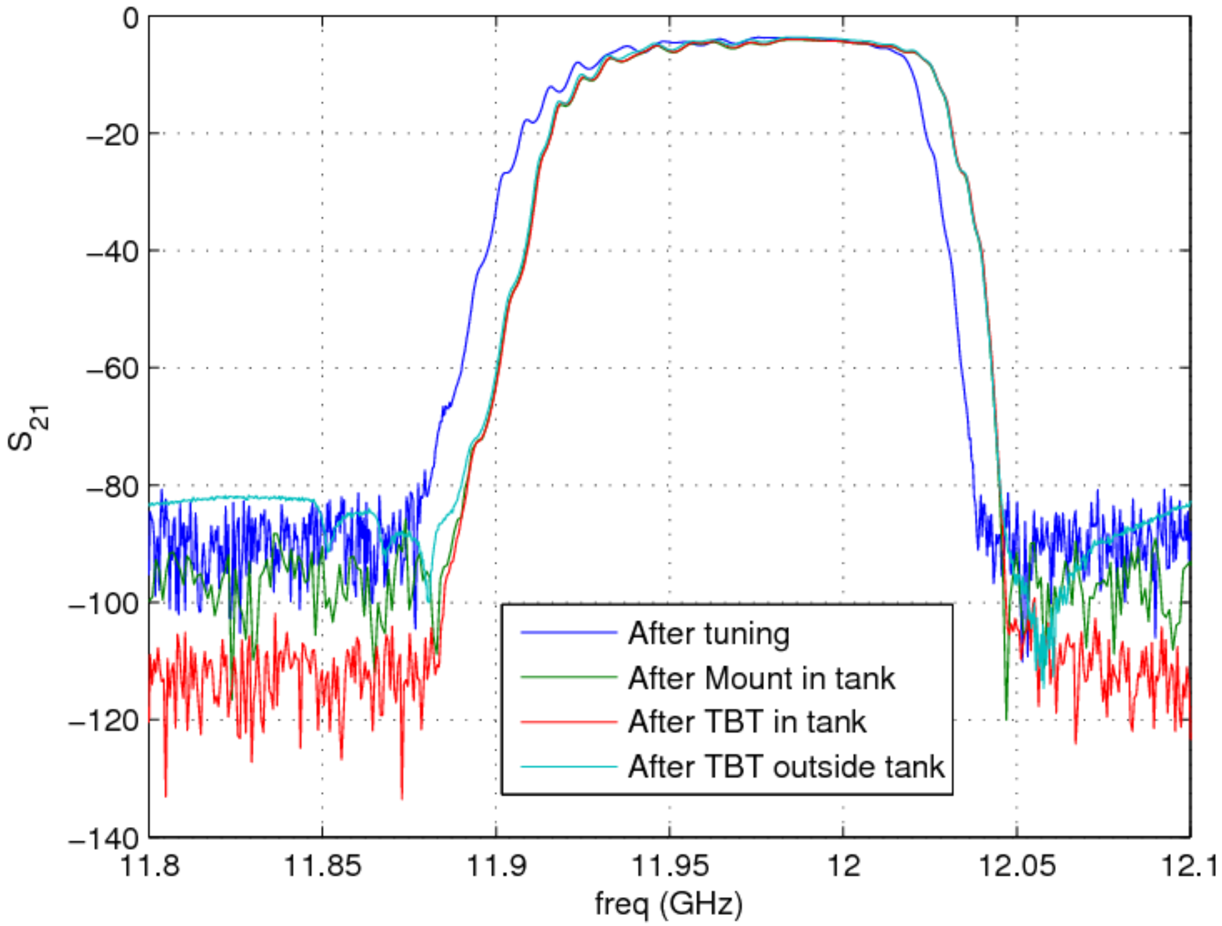
S. Doebert, December 1, 2010

Squeezing resonant frequency with bricolage heating !

The peak 106 MV/m gradient was achieved only after heating the accelerating frequency, by attaching heated water of 60 deg to accelerating structure cooling loop. This is estimated to lower the resonance frequency by 6 MHz.



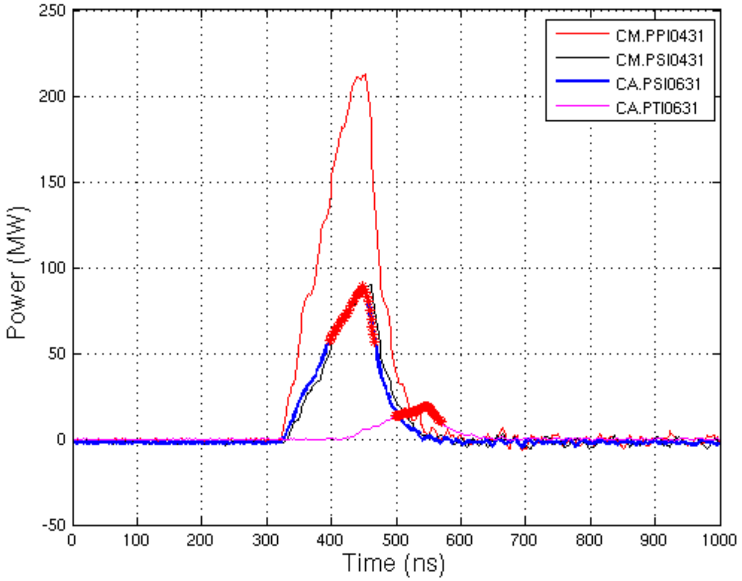
Shutdown measurements: structure detuning confirmed



- 10 MHz structure detuning after Two-Beam Tests confirmed in shutdown measurements (Jan 2011)
- Possible cause: deformation/squashing when clamping the cooling circuit onto the structure.

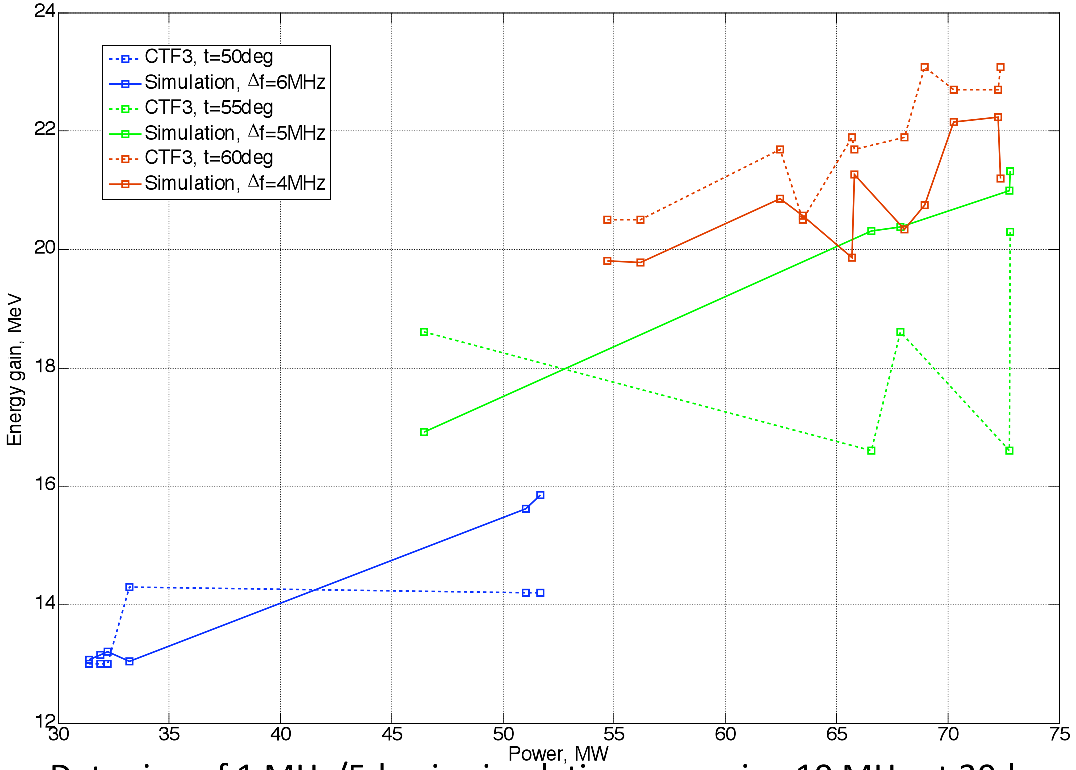
Reconstruction of voltage from rf input

For detailed energy budgets we need to take into account the TBTS non-flat rf pulse shape (due to rf recirculation), the operating conditions, using a model of the accelerating structure taking into account the detuning.



The TD24 accelerating structure has a fill time of 65 ns. **The time synchronization** between probe beam and rf was performed by moving the time slot window of the laser pulse picker (by steps of about 10 ns or less) and probe beam klystron by steps of 52 ns. Scanning the two knobs until peak acceleration is measured.

Example of reconstructed and measured acceleration, taking into account real rf pulse and detuning.

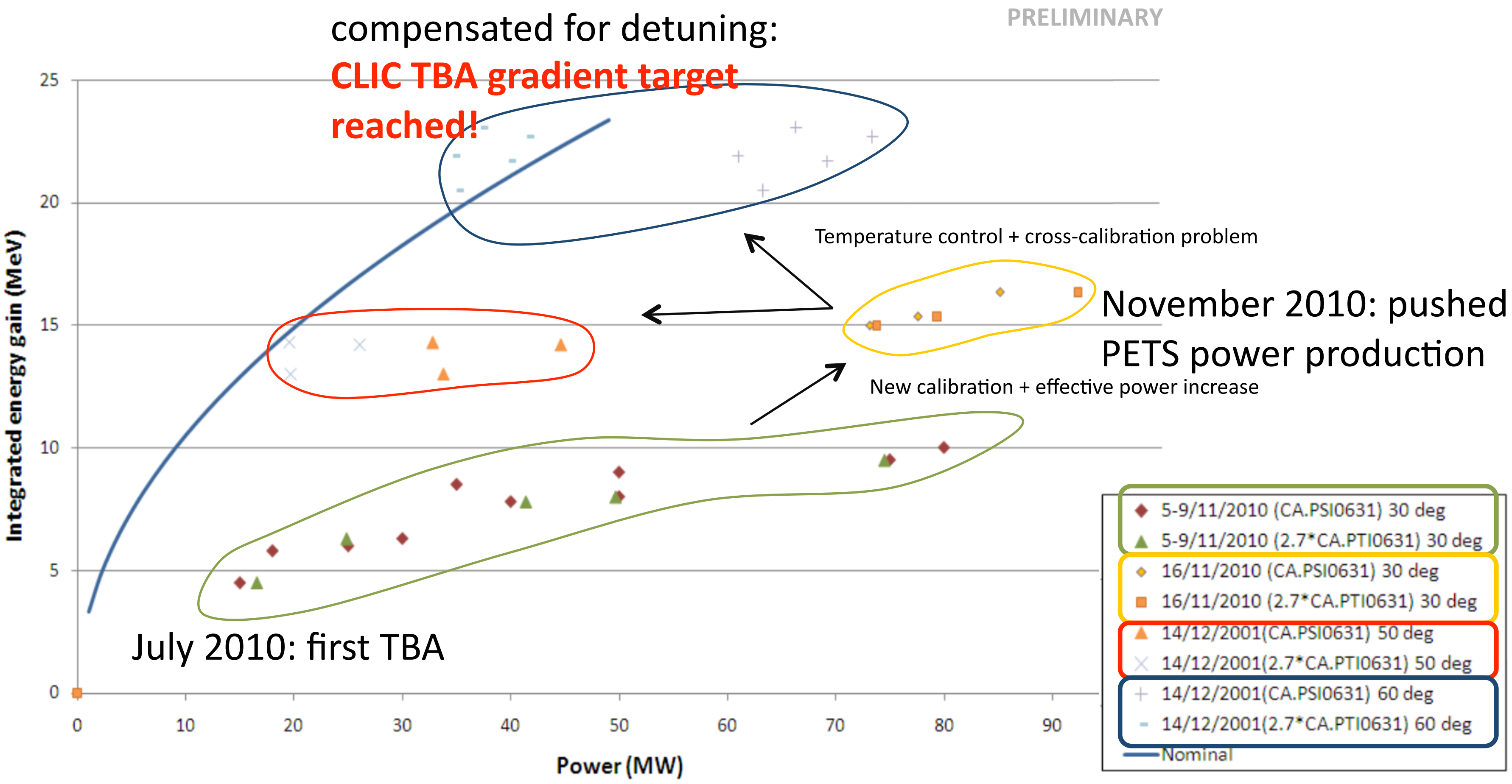


Detuning of 1 MHz/5deg in simulation, assuming 10 MHz at 30deg

Oleksiy Kononenko, Feb 2011

Summary: Two-Beam Acceleration experiments 2010

Two-Beam Acceleration Test - History



December 2010:

compensated for detuning:

CLIC TBA gradient target reached!

Temperature control + cross-calibration problem

November 2010: pushed PETS power production

New calibration + effective power increase

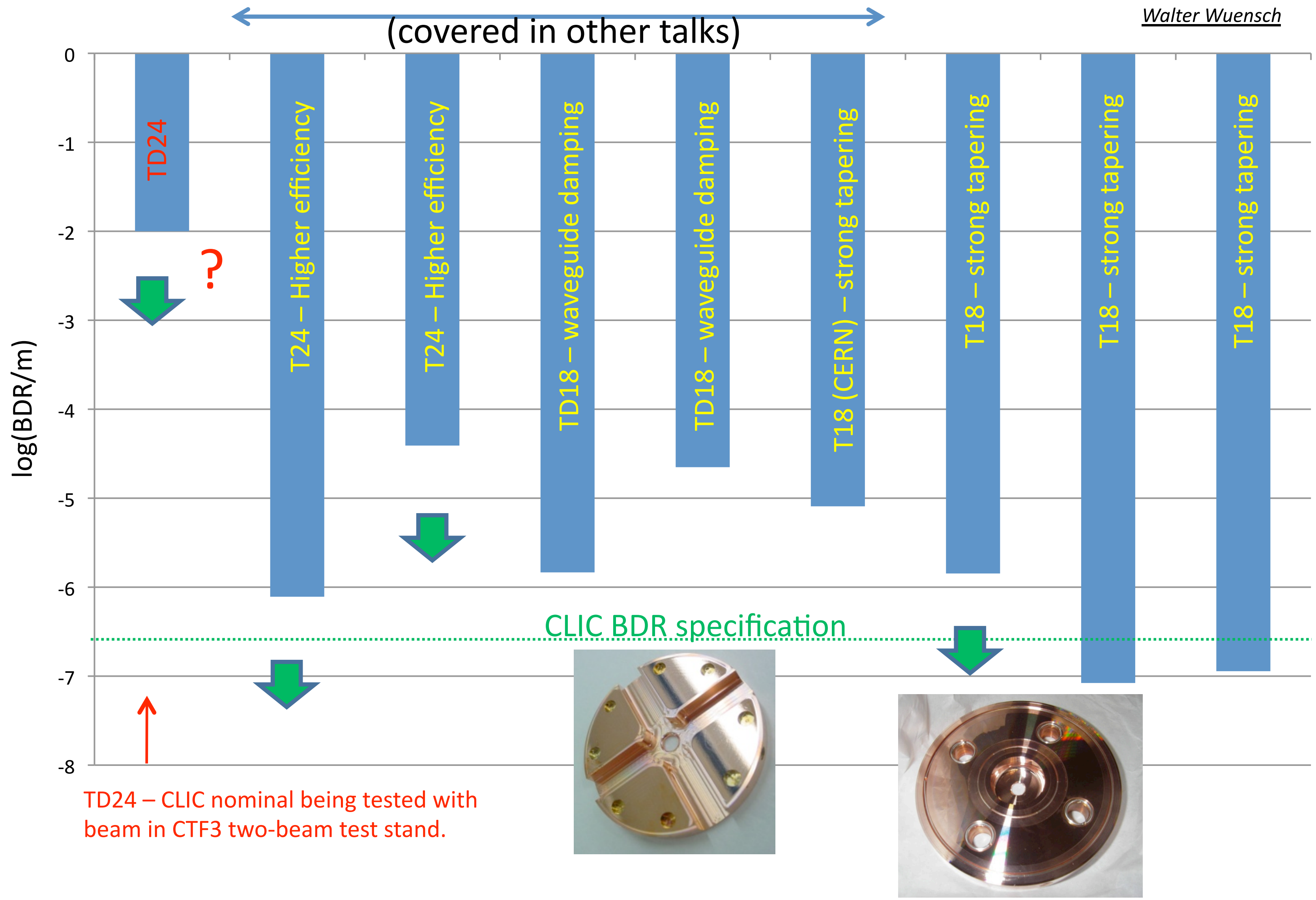
July 2010: first TBA

Javier Barranco, 2011

Two-Beam experiments compared to rf tests

Breakdown rate at 100 MV/m (unloaded) accelerating gradient and scaled to 180 ns pulse length

Walter Wuensch



TD24 – CLIC nominal being tested with beam in CTF3 two-beam test stand.

Two-Beam-Test Stand: plans for 2011

Continue Two-Beam Acceleration experiments :

- Will attempt to re-tune and re-install TD24 [back up solution: install an available T24]
- Without detuning, nominal 100 MV/m should be easily reached with CLIC pulse length (x 4 combination) -> will allow for better break down rate estimates [but not more than few 10^5 pulses, personal estimate]
- Full study of power, deceleration and acceleration budgets

Other TBTS activities :

- PETS On/Off mechanism
- Kick measurements
- Break down measurements in accelerating structure and PETS (next slide)

Additional CTF3 activities :

- Further drive beam generation optimization and stabilization
- Multi-PETS deceleration experiments (Test Beam Line), up to 8 PETS in 2011
- Photo injector tests (PHIN)

In addition at SLAC/KEK/CERN :

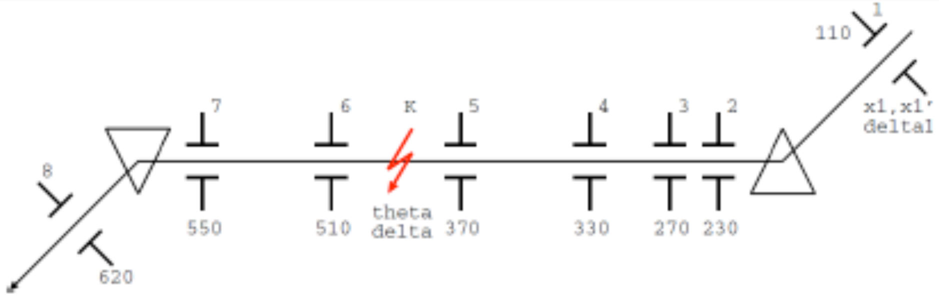
- High power structure tests, including TD24 (see next talks)
- CERN: on-line this year with 12 GHz Klystron Test Stand (~ summer 2011?)

Planned kick and break down measurements

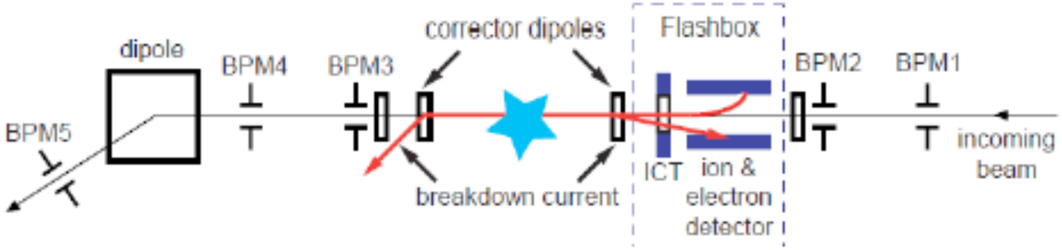
- Measurements of beam kick due to HOM and RF breakdowns both on the drive beam and on the probe beam
  (10 µm BPMs resolution for 10 mrad angular resolution)

already in 2009 for the drive beam without considering incoming energy variation

(CTF3-Note-098)



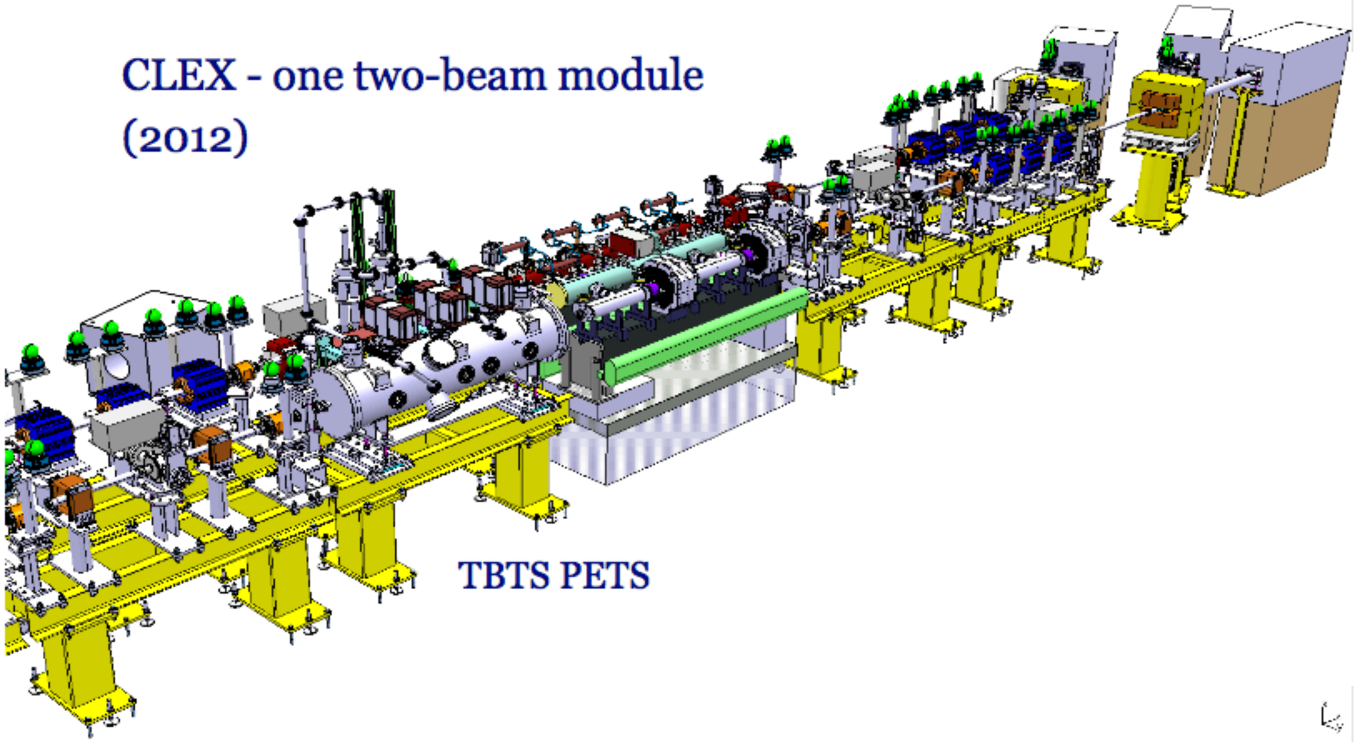
- better understanding of the breakdown process with:
  - indirect RF measurements (reflection during breakdowns);
  - direct measurements of emitted electrons and ions (flashbox).

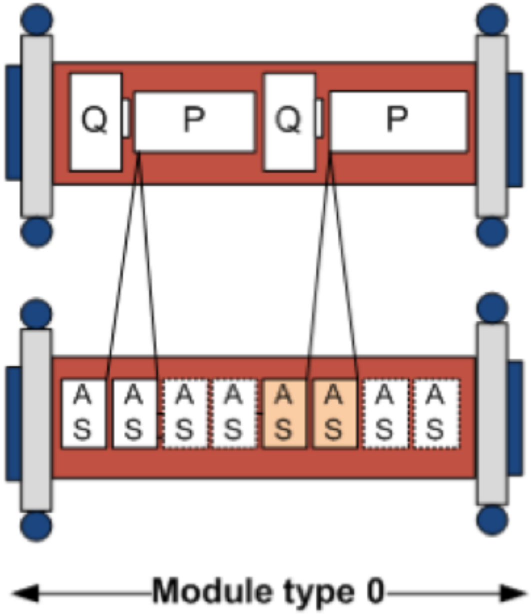


Andrea Palaia et al. Uppsala University

CTF3+ : first update plans (2012)

- First upgrade of CTF3 two-beam acceleration test: **adding one full CLIC-type module**, in addition to TBTS.





- Realistic beam **tests of a module** with all relevant components in CLEX.
- Next step after this: 3 CLIC modules chained together
- Then: N CLIC modules

Conclusions

- **2010: a year of very good progress for CTF3, despite a 4 months start-up delay due to a fire**
    - Demonstrated the CLIC gradient of 100 MV/m in a reproducible way
    - Hard work and clever ideas (heating station...) allowed to reach the target despite a significant ~10 MHz structure detuning
    - Optimized and increased stability of CTF3 drive beam generation by flattening beam phase and adding current and phase feedbacks
    - Better precision of power production and deceleration measurements

- **2011: a lot of interesting work to be done, including**
    - Stable Two-Beam Acceleration with a non-detuned structure
    - Understanding transverse effects observed in accelerating structure
    - PETS on/off
    - Break down rate measurements in two-beam acceleration
    - TBTS kick measurements and break down experiments

- **2012+: program to upgrade TBTS to a full-fledged CLIC TBA demo (3+ modules)**

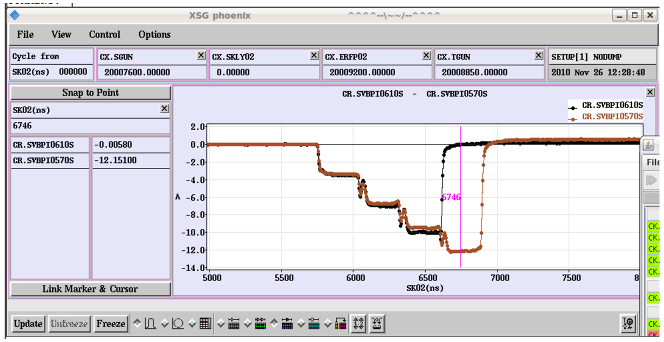
Extras

TBTS: example of drive beam stability

Example of TBTS signal pulse to pulse jitter, and along the pulse signals

- Taken from measurements day for characterization of power and deceleration (machine optimized for stability, x 4 combination)
- My opinion: beam transport and stability this day good day quite good with respect to year (but cannot say whether it was one of the best)

(Nov 26, 2010)



Cycle from SK02(ns) 000000

CX.SGUN 20007600.00000

CX.SKLY02 0.00000

CX.ERFP02 20009200.00000

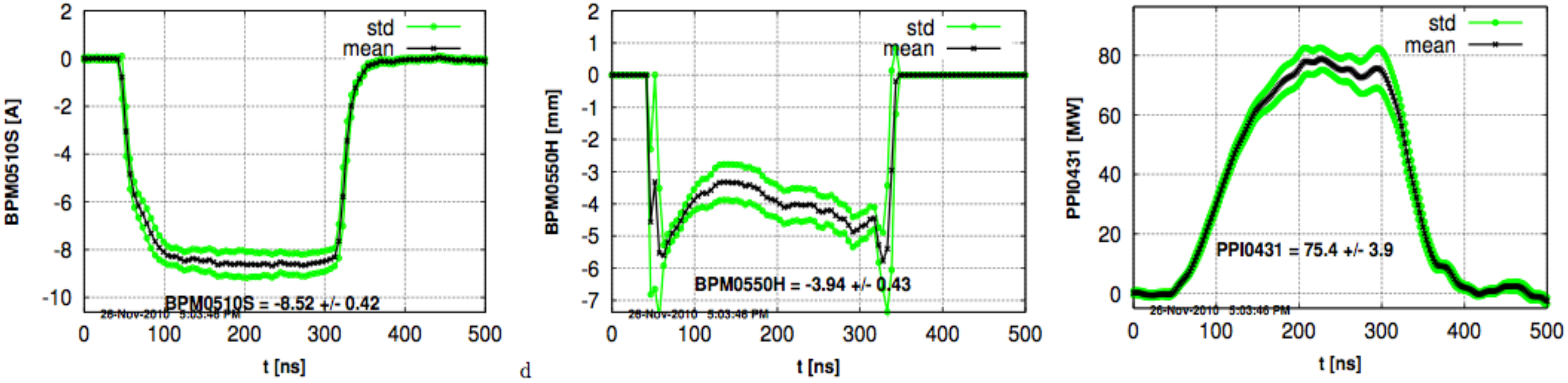
CX.TGUN 20008850.00000

SETUP[1] NODUMP 2010 Nov 26 12:28:48

SK02(ns) 6746

CR.SVBPI0610S -0.00580

CR.SVBPI0570S -12.15100



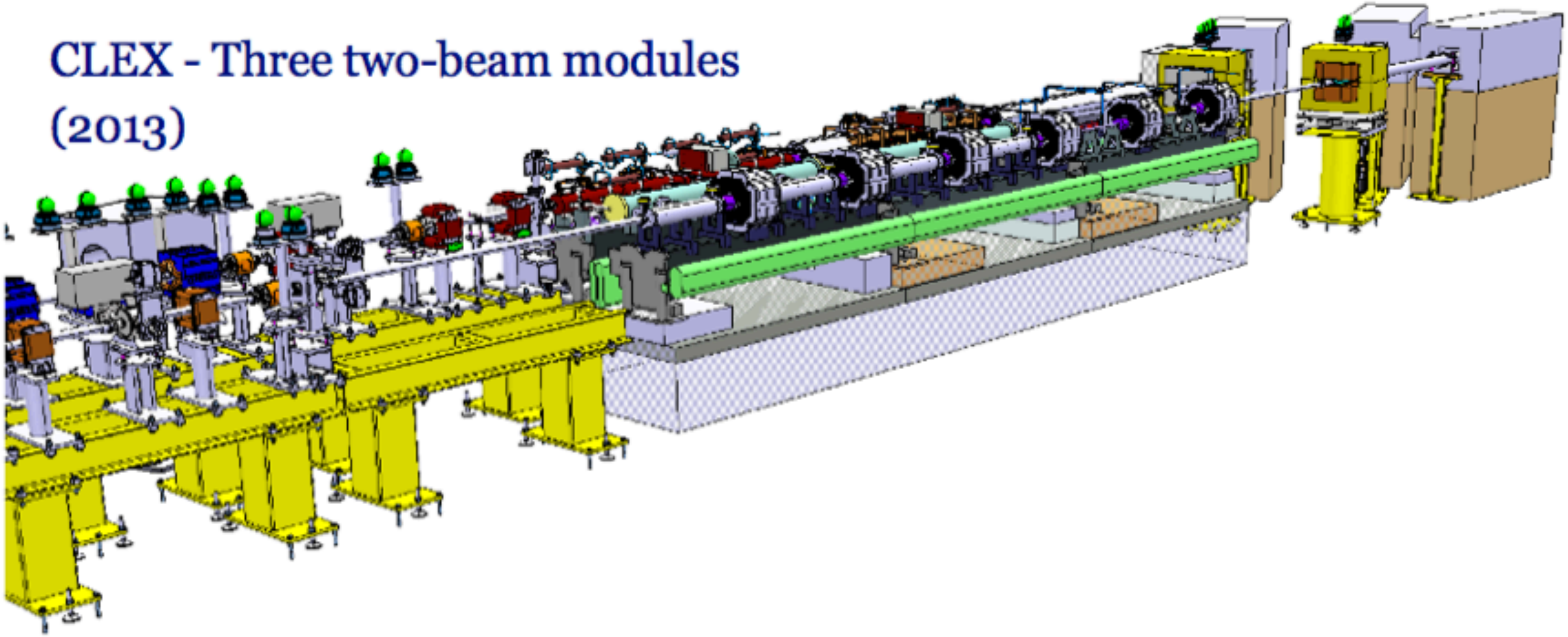
Shown: 1) current just after PETS, 2) H position just before spectrometer, 3) power in PETS loop :

- quite nice and flat current top of over > 200 ns
- many % pulse to pulse jitter
- dispersion not under control
- significant losses from ring to TBTS

E. Adli, Nov 2010

CTF3+ : future plans

- Second upgrade of CTF3 two-beam acceleration tests: **adding two more CLIC-type modules**

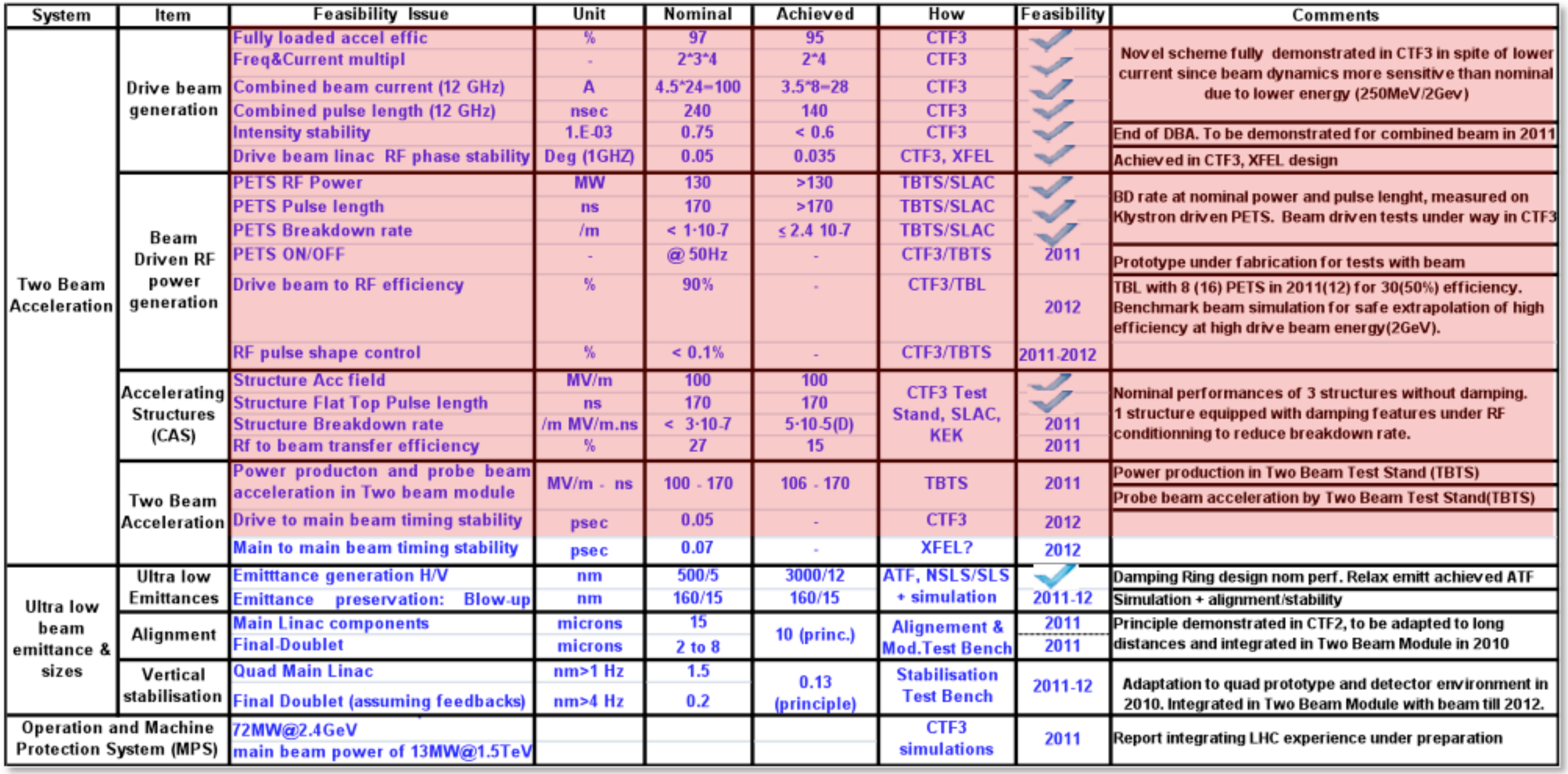


CLEX - Three two-beam modules (2013)

- Clear goal: realistic beam tests of different modules (type 0 and type 1) + interconnections.
- Optics: aperture limitations now start to become more challenging
- Power: drive beam limitations, (25/100)^2 ~ 1/16 is still a challenge

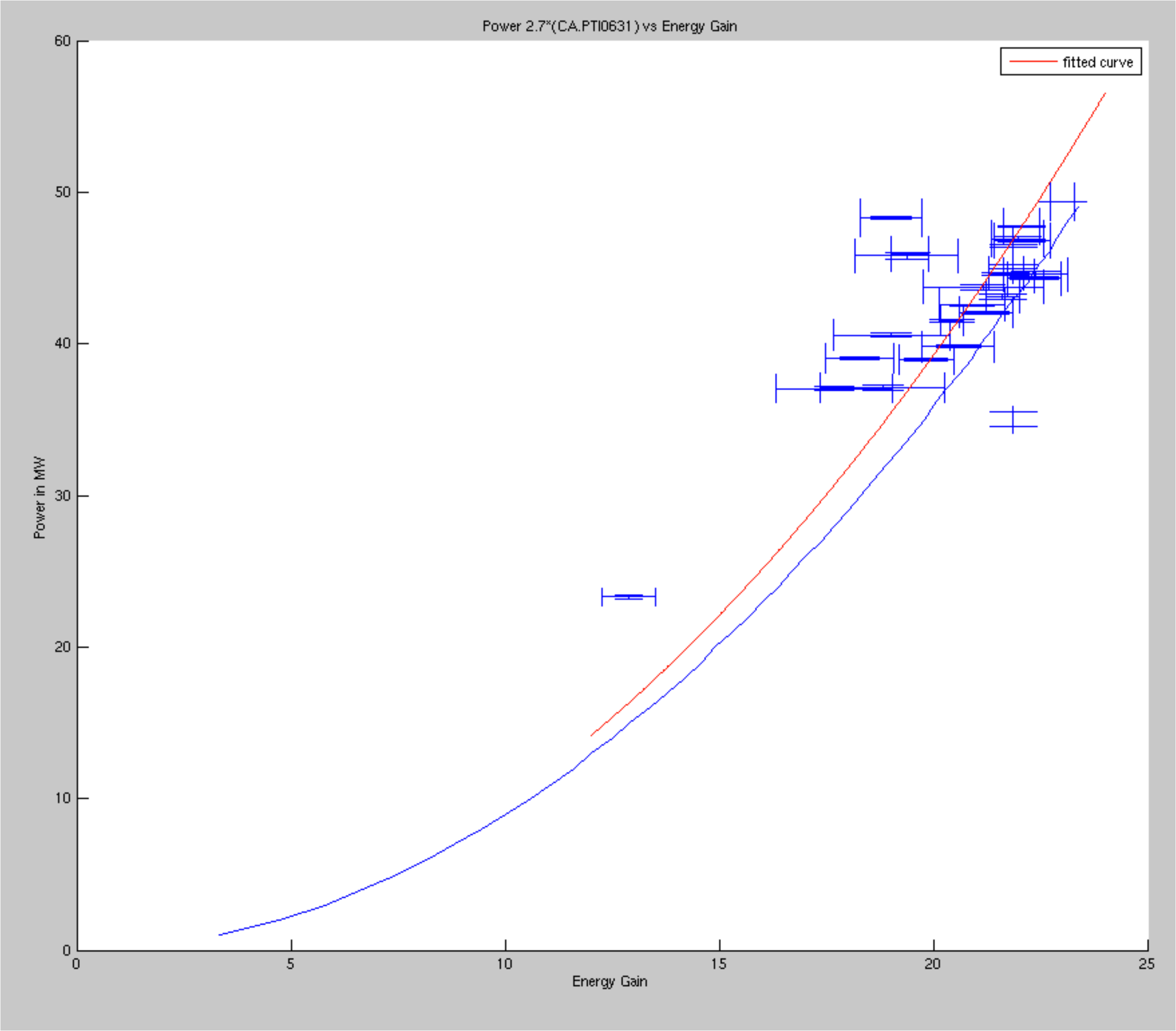
CTF3 achievements summary

CTF3



System	Item	Feasibility Issue	Unit	Nominal	Achieved	How	Feasibility	Comments
Two Beam Acceleration	Drive beam generation	Fully loaded accel effic	%	97	95	CTF3	✓	Novel scheme fully demonstrated in CTF3 in spite of lower current since beam dynamics more sensitive than nominal due to lower energy (250MeV/2Gev)
		Freq&Current multipl	-	2*3*4	2*4	CTF3	✓	
		Combined beam current (12 GHz)	A	4.5*24=100	3.5*8=28	CTF3	✓	
		Combined pulse length (12 GHz)	nsec	240	140	CTF3	✓	
		Intensity stability	1.E-03	0.75	< 0.6	CTF3	✓	End of DBA. To be demonstrated for combined beam in 2011
		Drive beam linac RF phase stability	Deg (1GHZ)	0.05	0.035	CTF3, XFEL	✓	Achieved in CTF3, XFEL design
	Beam Driven RF power generation	PETS RF Power	MW	130	>130	TBTS/SLAC	✓	BD rate at nominal power and pulse lenght, measured on Klystron driven PETS. Beam driven tests under way in CTF3
		PETS Pulse length	ns	170	>170	TBTS/SLAC	✓	
		PETS Breakdown rate	/m	< 1·10-7	≤ 2.4 10-7	TBTS/SLAC	✓	
		PETS ON/OFF	-	@ 50Hz	-	CTF3/TBTS	2011	Prototype under fabrication for tests with beam
		Drive beam to RF efficiency	%	90%	-	CTF3/TBL	2012	TBL with 8 (16) PETS in 2011(12) for 30(50%) efficiency. Benchmark beam simulation for safe extrapolation of high efficiency at high drive beam energy(2GeV).
		RF pulse shape control	%	< 0.1%	-	CTF3/TBTS	2011-2012	
	Accelerating Structures (CAS)	Structure Acc field	MV/m	100	100	CTF3 Test Stand, SLAC, KEK	✓	Nominal performances of 3 structures without damping. 1 structure equipped with damping features under RF conditionning to reduce breakdown rate.
		Structure Flat Top Pulse length	ns	170	170		✓	
		Structure Breakdown rate	/m MV/m.ns	< 3·10-7	5·10-5(D)		2011	
		Rf to beam transfer efficiency	%	27	15		2011	
	Two Beam Acceleration	Power producton and probe beam acceleration in Two beam module	MV/m - ns	100 - 170	106 - 170	TBTS	2011	Power production in Two Beam Test Stand (TBTS) Probe beam acceleration by Two Beam Test Stand(TBTS)
		Drive to main beam timing stability	psec	0.05	-	CTF3	2012	
		Main to main beam timing stability	psec	0.07	-	XFEL?	2012	
Ultra low beam emittance & sizes	Ultra low Emittances	Emitttance generation H/V	nm	500/5	3000/12	ATF, NSLS/SLS + simulation	✓	Damping Ring design nom perf. Relax emitt achieved ATF
		Emittance preservation: Blow-up	nm	160/15	160/15		2011-12	Simulation + alignment/stability
	Alignment	Main Linac components	microns	15	10 (princ.)	Alignement & Mod.Test Bench	2011	Principle demonstrated in CTF2, to be adapted to long distances and integrated in Two Beam Module in 2010
		Final-Doublet	microns	2 to 8			2011	
	Vertical stabilisation	Quad Main Linac	nm>1 Hz	1.5	0.13 (principle)	Stabilisation Test Bench	2011-12	Adaptation to quad prototype and detector environment in 2010. Integrated in Two Beam Module with beam till 2012.
		Final Doublet (assuming feedbacks)	nm>4 Hz	0.2				
Operation and Machine Protection System (MPS)		72MW@2.4GeV				CTF3 simulations	2011	Report integrating LHC experience under preparation
		main beam power of 13MW@1.5TeV						

Reproducible CLIC target gradient shown

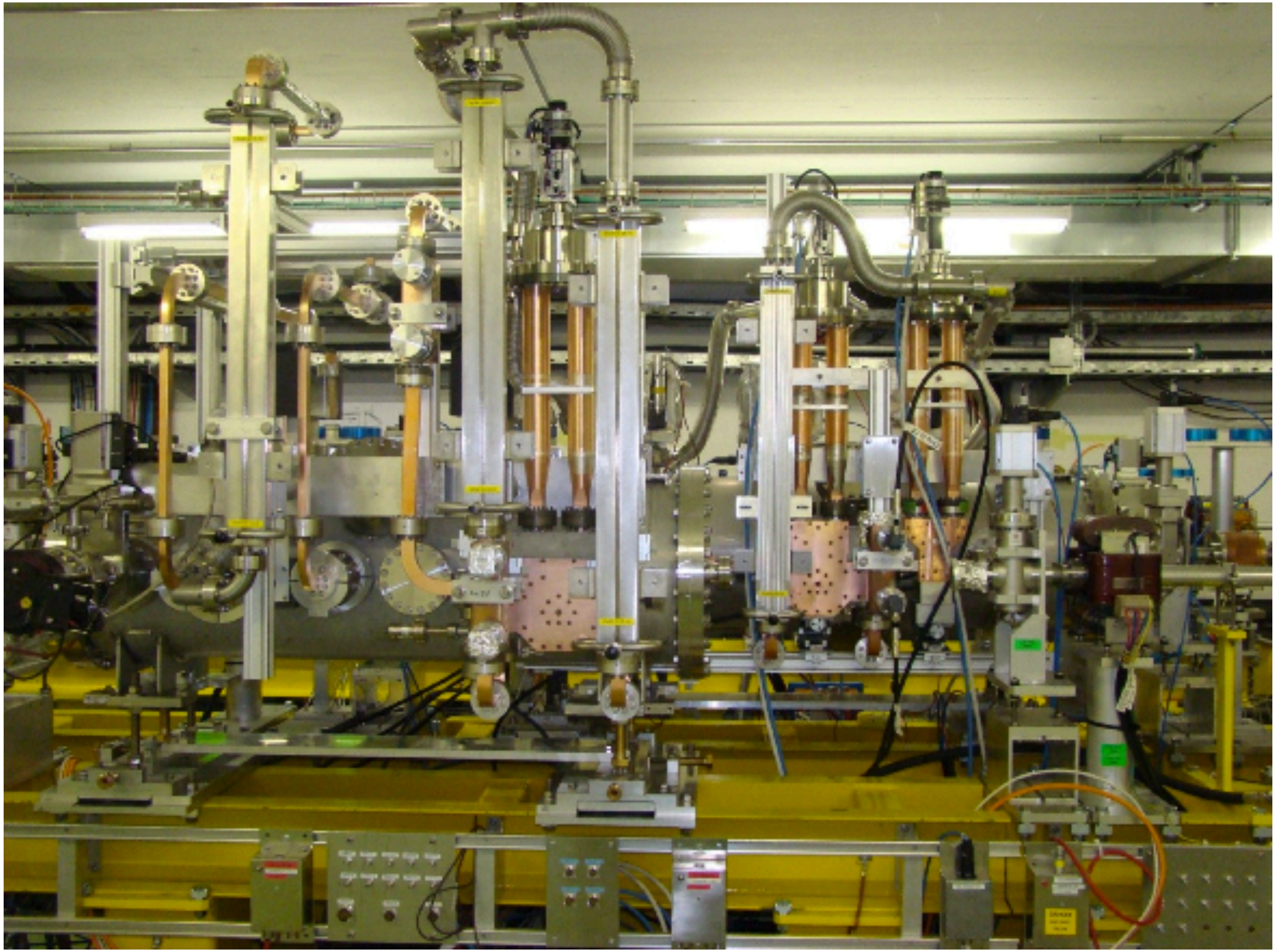


Gradients above CLIC target continously reproducible.

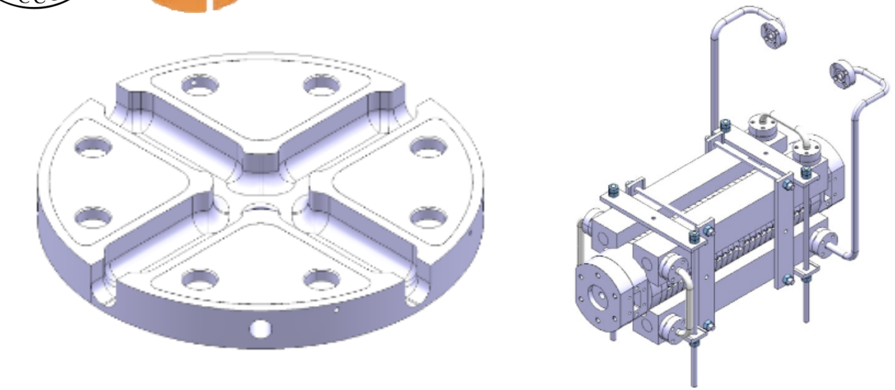
According to rf measurements, an input power several factors larger than expected required for this gradient.

(T. Persson, December 14, 2010)

TD24 (front) and PETS tank in CLEX Two-Beam Test Stand



Details for installed TD24 TBTS accelerating structure

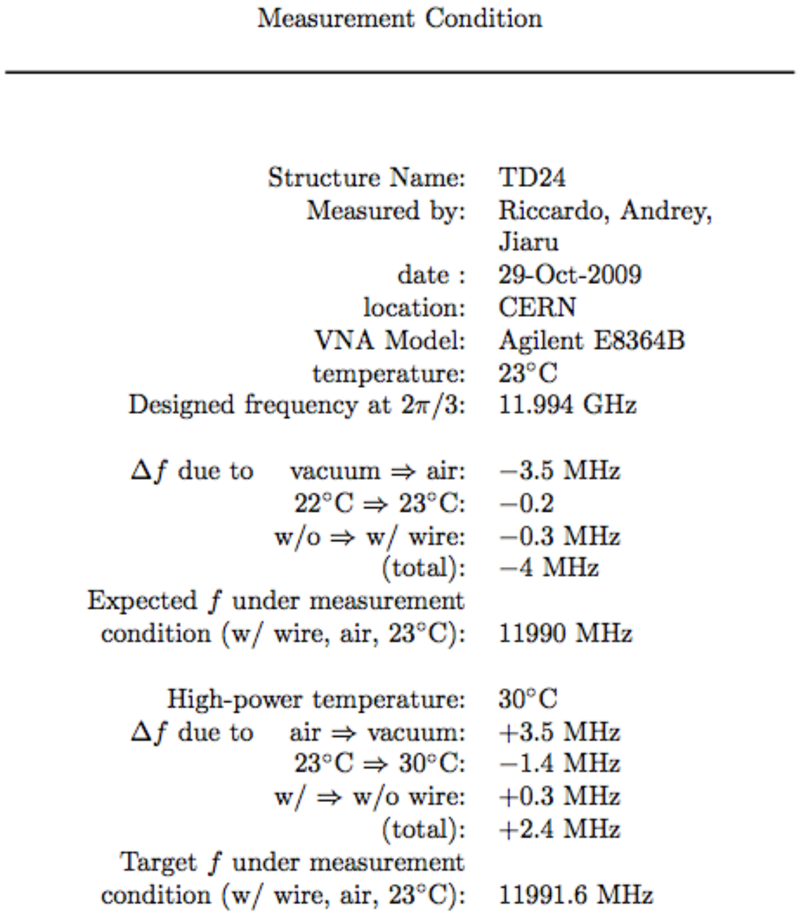


Bonded at 1000 deg (design for brazed)

	120°/cell		comments
f [GHz]	11.995		
S12	0.6542		
t_f [ns]	64.55		
Q^{Cu}	5732		
Gradient averaged over all cells			
V_{26} [V]@P_{in} = 1 W	3340		2 matching +24 regular cells L_{acc} = 227.7 mm,
G_{26} [V/m]@P_{in} = 1 W	14661		
P_{in} [MW]@<G_{26}=100MV/m>	46.5		
Gradient averaged over regular cells only			
V_{24} [V]@P_{in} = 1 W	3078		24 regular cells only L_{acc} = 200.0 mm,
G_{24} [V/m]@P_{in} = 1 W	15390		
P_{in} [MW]@<G_{24}=100MV/m>	42.2		

A. Grudiev, RF design and parameters of 12 GHz TD24_vg1.8_disk

https://edms.cern.ch/document/1070498/1



Measurement Condition

Structure Name:	TD24
Measured by:	Riccardo, Andrey, Jiaru
date :	29-Oct-2009
location:	CERN
VNA Model:	Agilent E8364B
temperature:	23°C
Designed frequency at $2\pi/3$:	11.994 GHz
Δf due to vacuum ⇒ air:	−3.5 MHz
22°C ⇒ 23°C:	−0.2
w/o ⇒ w/ wire:	−0.3 MHz
(total):	−4 MHz
Expected f under measurement condition (w/ wire, air, 23°C):	11990 MHz
High-power temperature:	30°C
Δf due to air ⇒ vacuum:	+3.5 MHz
23°C ⇒ 30°C:	−1.4 MHz
w/ ⇒ w/o wire:	+0.3 MHz
(total):	+2.4 MHz
Target f under measurement condition (w/ wire, air, 23°C):	11991.6 MHz

“After tuning, the frequency of 2pi/3 mode at 30 ◦C vacuum is now 11995.8 MHz “

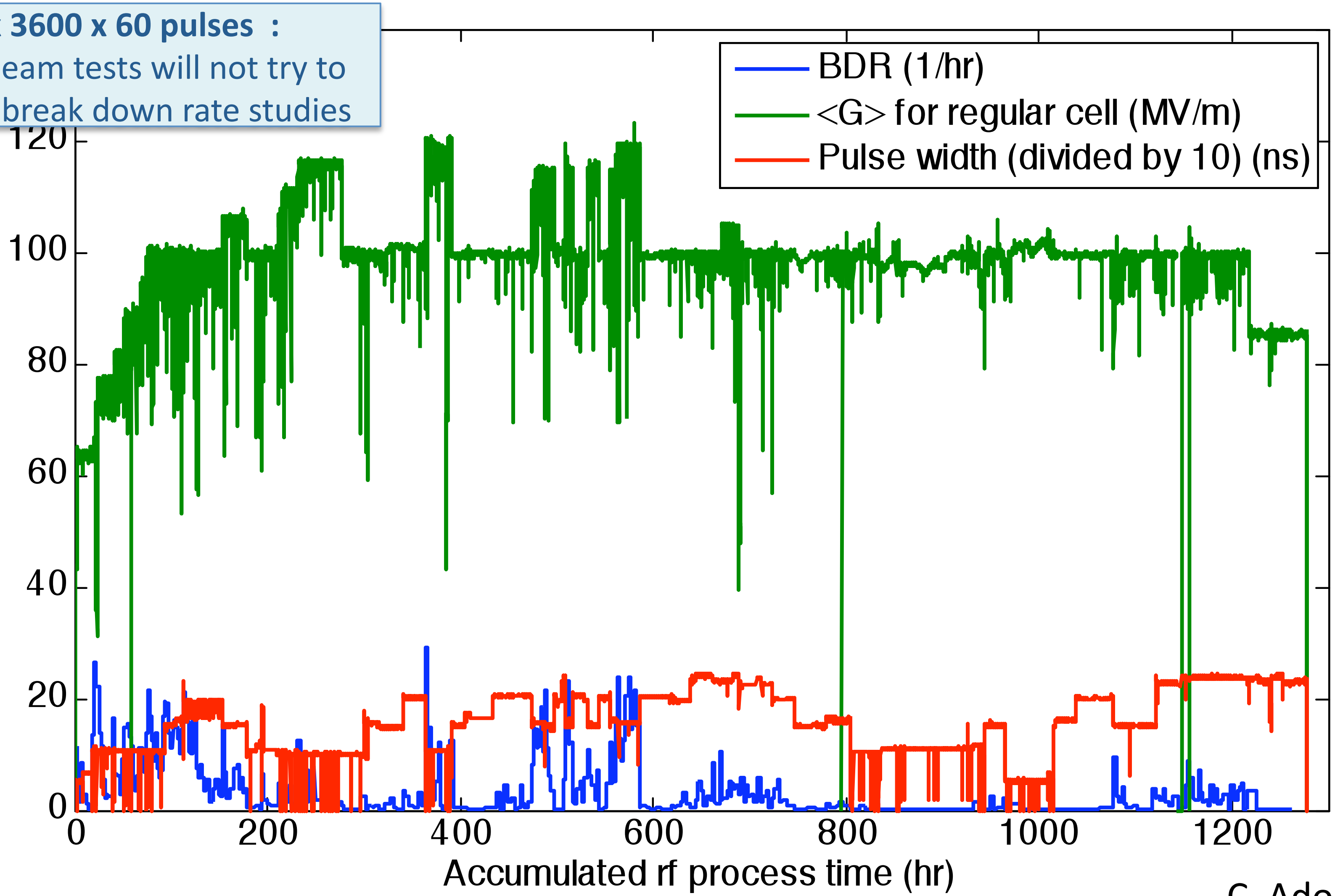
J. Shi, 12WDSDvg1.8Cu No2 (TD24 No2 12GHz)
RF Measurement Results after tuning

https://edms.cern.ch/document/1051875/1

Rf tests at SLAC/KEK

Typical Operation History

1200 x 3600 x 60 pulses :
TBTS beam tests will not try to mimic break down rate studies



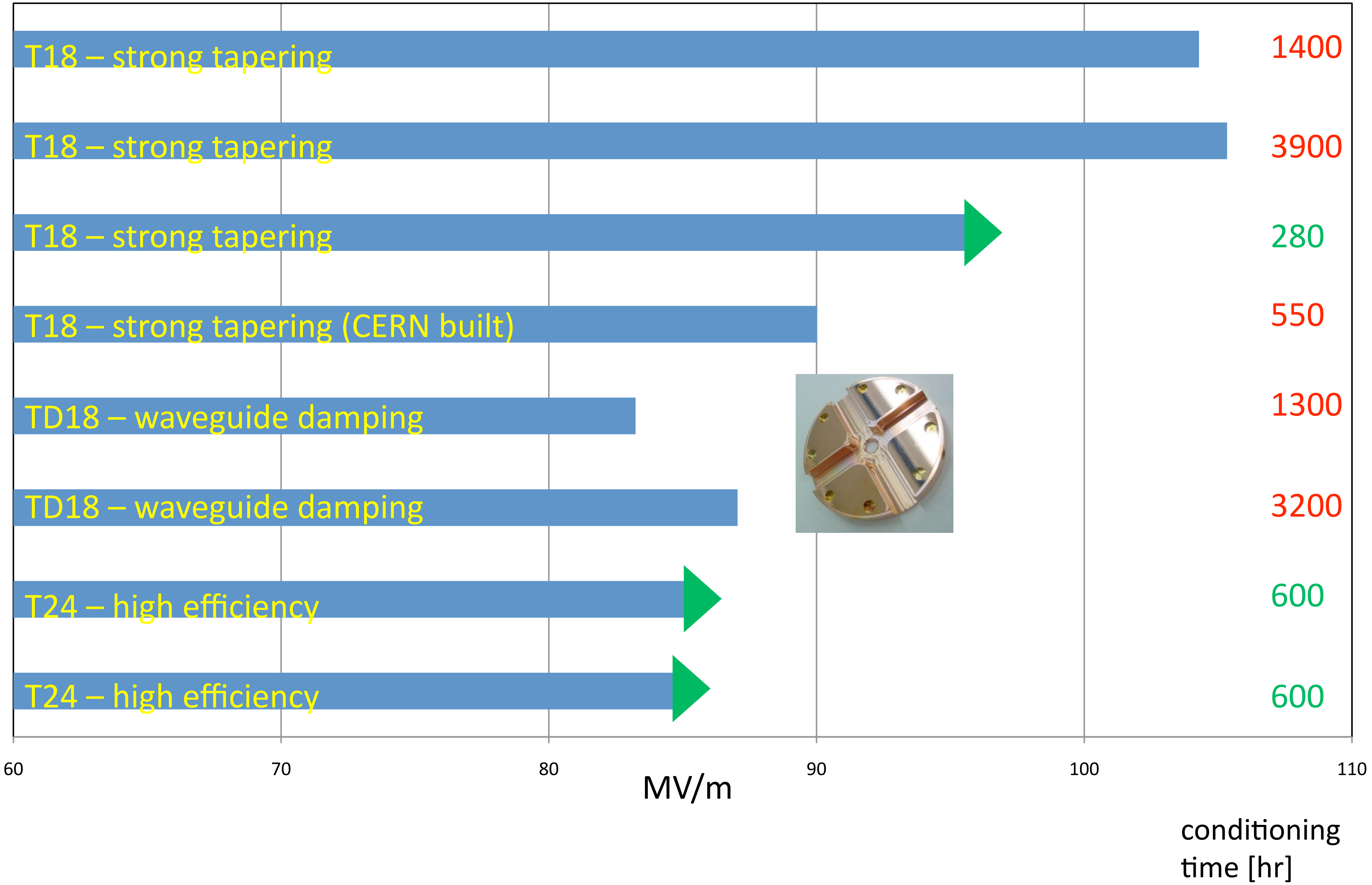
Final Run at 230 ns: 94 hrs at 100 MV/m w BDR = 7.6e-5
60 hrs at 85 MV/m w BDR = 2.4e-6

TD18

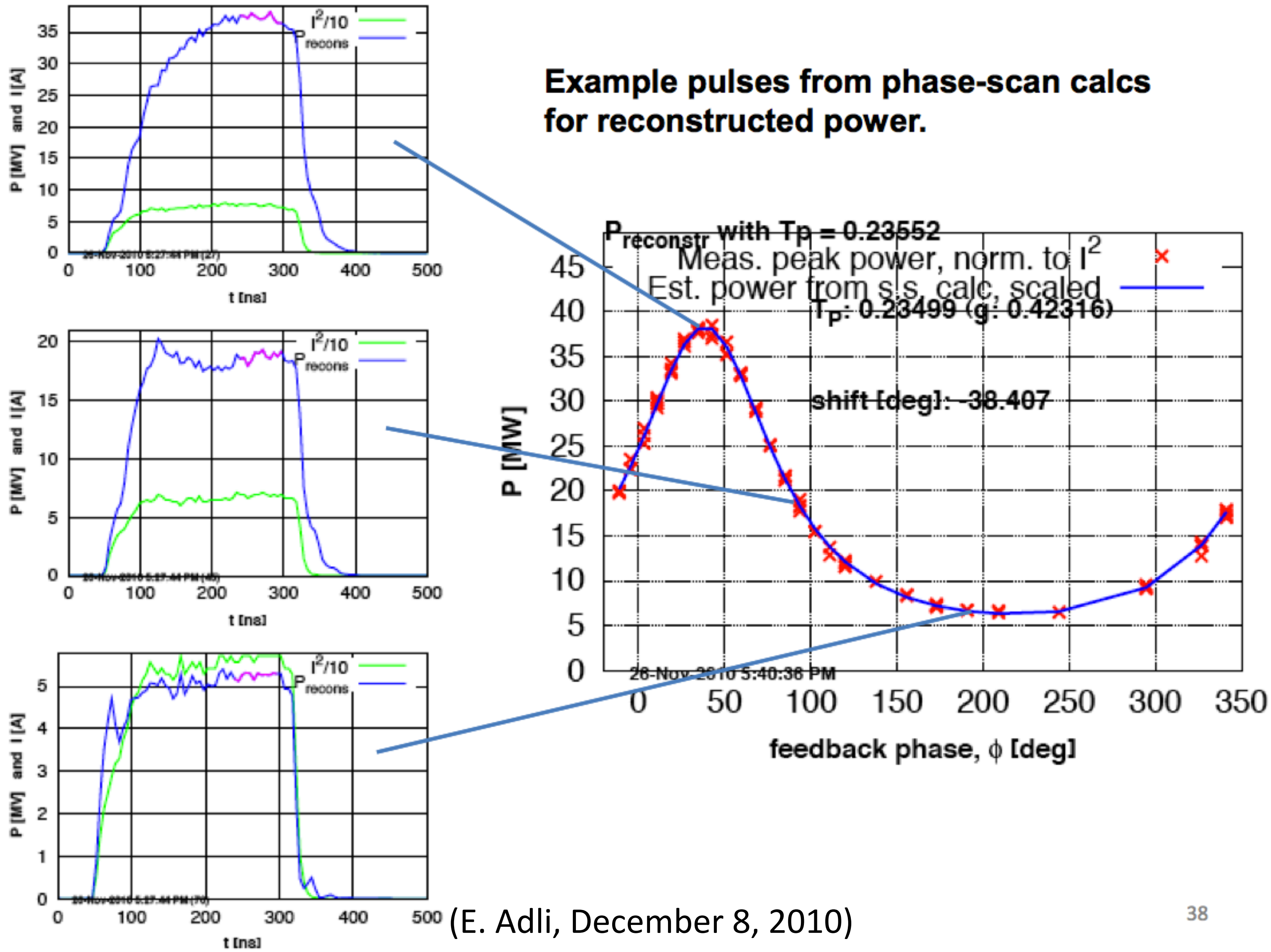
C. Adolphsen
F. Wang
SLAC

Rf tests at SLAC/KEK

Gradient at CLIC $4*10^{-7}$ BDR and 180 ns pulse length



Characterization of PETS power with resonant field recirculation



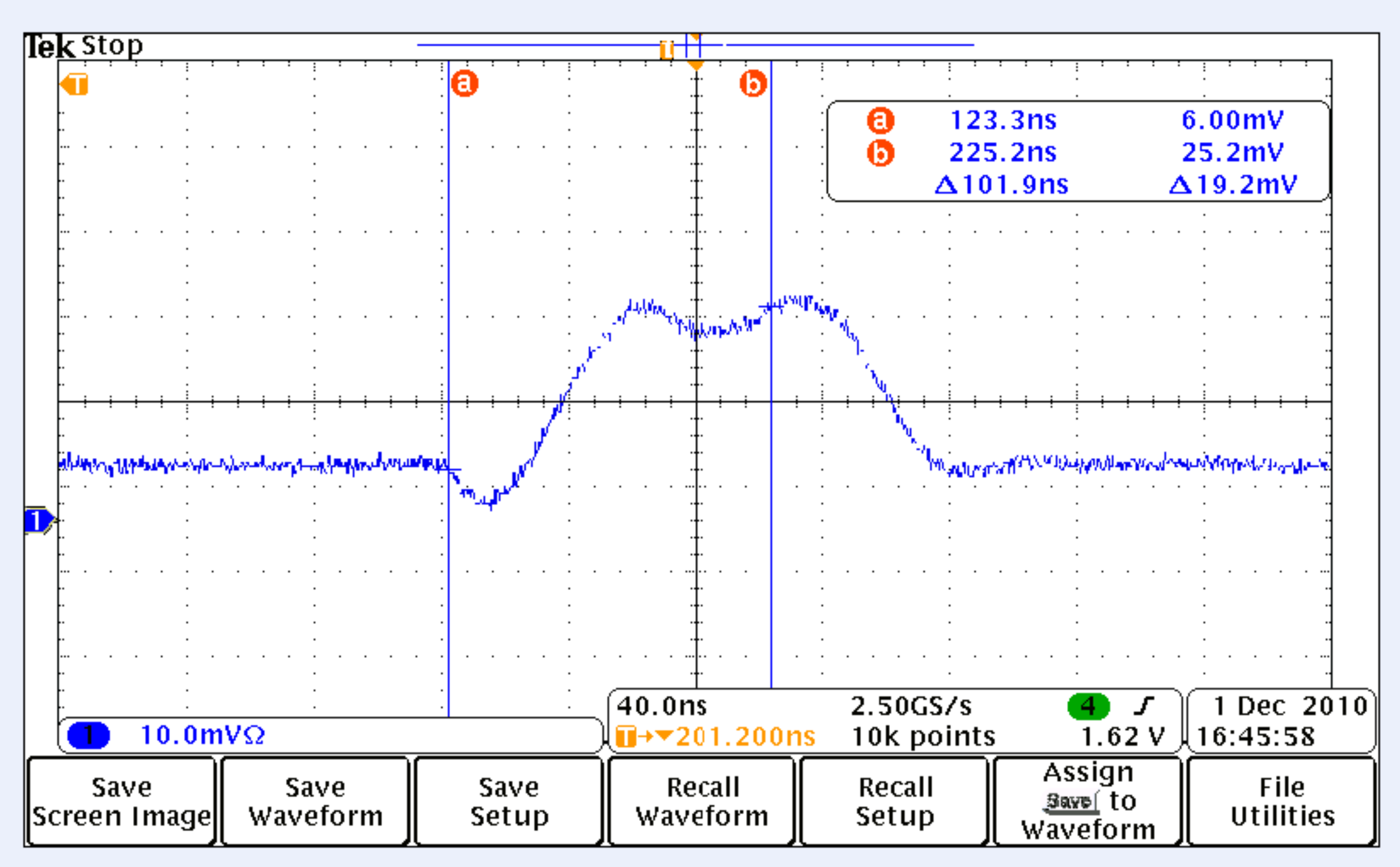
Example pulses from phase-scan calcs for reconstructed power.

(E. Adli, December 8, 2010)

Verification of detuning measurement

Sending long probe beam (~100 ns) with 11.994 MHz bunch spacing

Mixing with signal of 11.994 MHz



a	123.3ns	6.00mV
b	225.2ns	25.2mV
	Δ101.9ns	Δ19.2mV

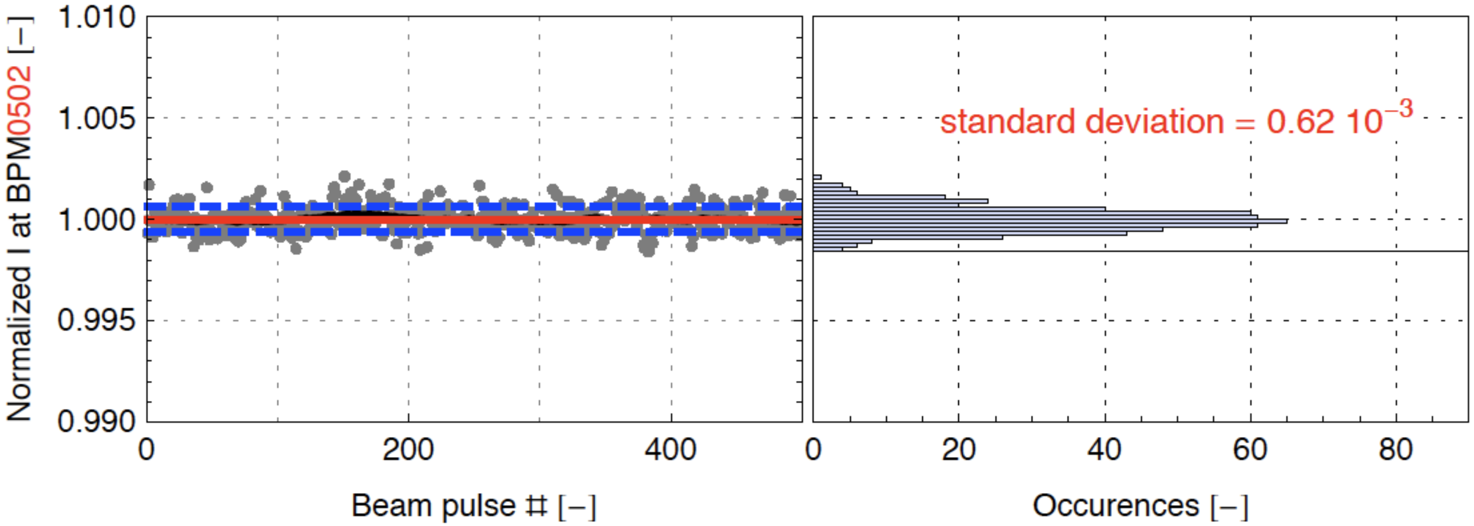
1 10.0mVΩ

40.0ns 2.50GS/s 4 ʃ 1 Dec 2010
T→▼201.200ns 10k points 1.62 V 16:45:58

(S. Doebert, December 1, 2010)

Achieved current stability

Guido Sterbini, Simona Bettoni, et al.



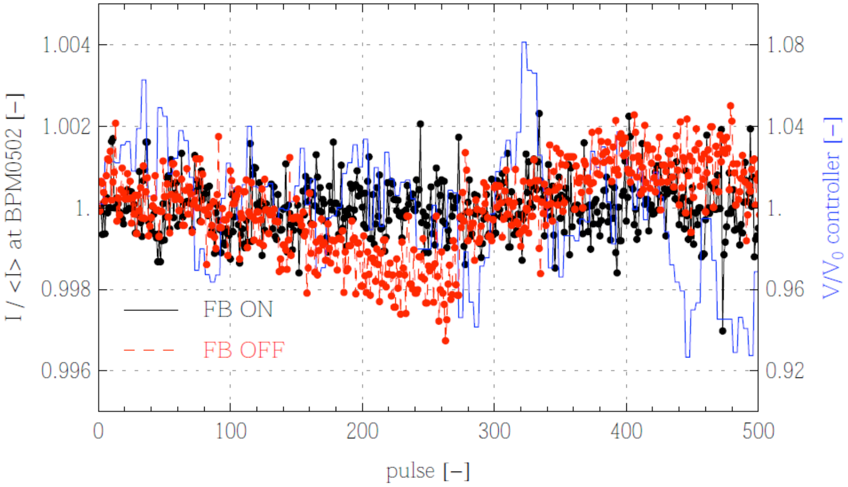
- New heater power supply, better set-point, improved measurement procedures

  ⇨ ΔI/I ~ 0.75 – 1 10^{-3}

- Gun feed-back

  ⇨ ΔI/I ~ 0.6 10^{-3} (or lower…)

Below CLIC DB specs!



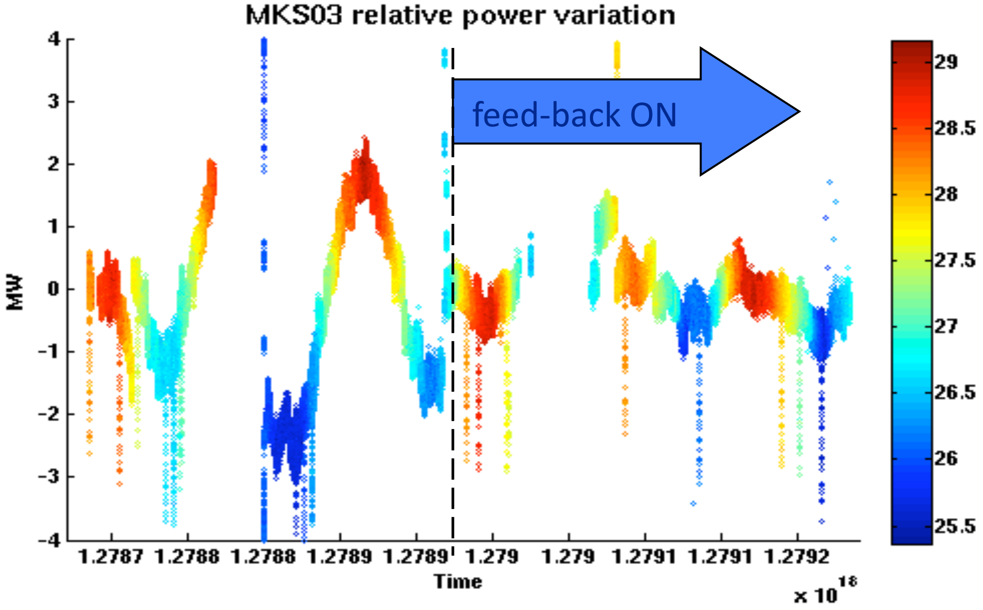
CTF3

Hardware upgrades, • Feed-back systems

- Improvements in low-level and high-power RF
- Gun improvements (new heater power supply, …)

- RF phase feedback – now fully operational
- RF temperature feedback for pulse compression

⇨ reproducibility, stability



Alexey Dubrovskiy

Feed-backs plus optics improvements…