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CLIC Feasibility Demonstration at CTF3

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KVI Groningen
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The Key to CLIC Efficiency

- NC Linac for 1.5 TeV/beam
  - accelerating gradient: **100 MV/m**
  - RF frequency: **12 GHz**
- Total active length for 1.5 TeV: **15 km**

  ➔ individual klystrons not realistic
- **Two-beam acceleration scheme**

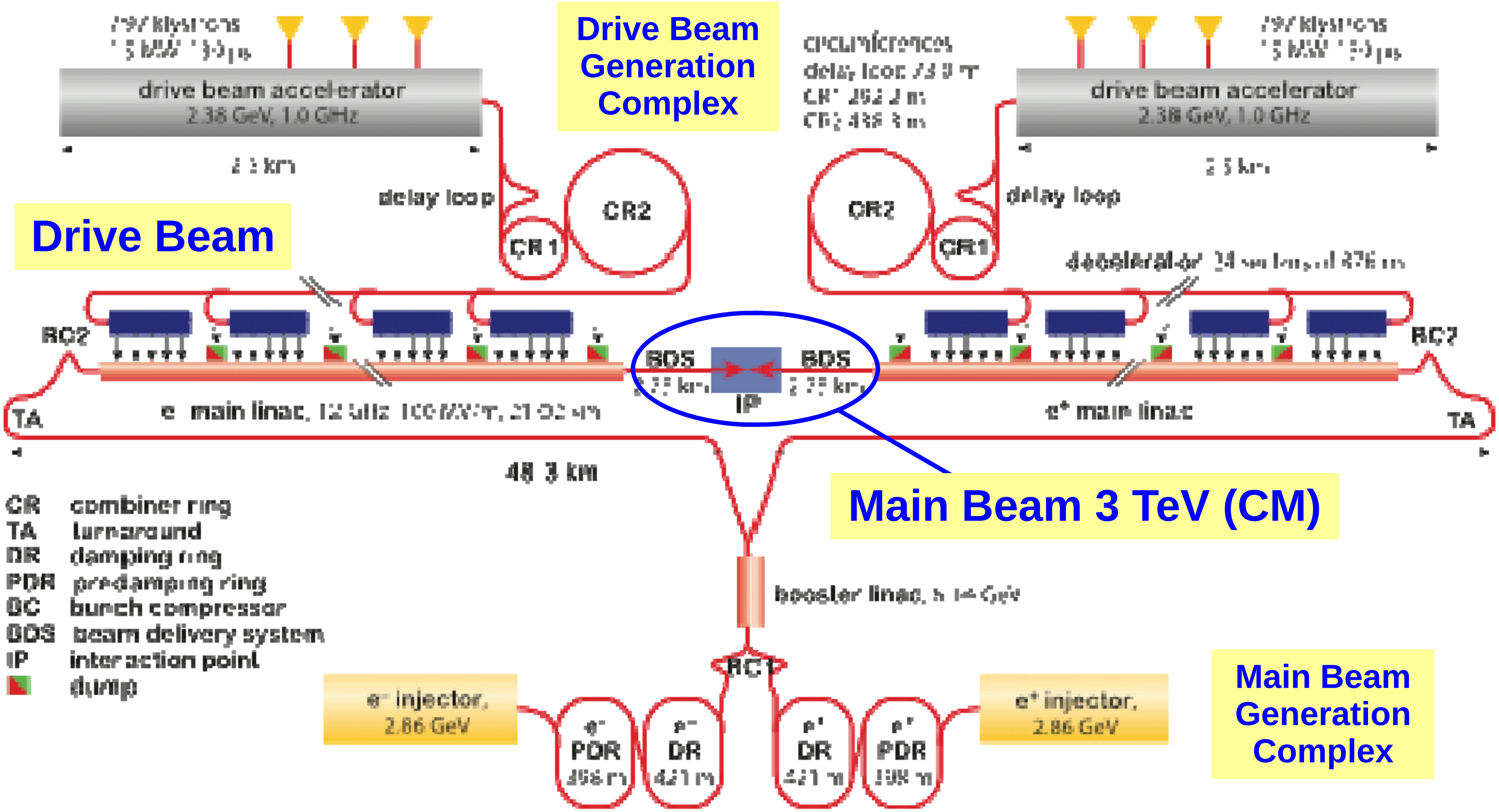
Main Linac	
C.M. Energy	3 TeV
Peak luminosity	2×10^{34} cm^{-2}s^{-1}
Beam Rep. rate	50 Hz
Pulse time duration	156 ns
Average gradient	100 MV/m
# cavities	2 x 71,548

- Luminosity of 2×10^{34} cm^{-2}s^{-1}
  - short pulse (156ns)
  - high rep-rate (50Hz)
  - very small beam size (1x100nm)

- 64 MW RF power / accelerating structure of 0.233m active length

  ➔ 275 MW/m
- Estimated wall power **415 MW** at 7% efficiency

CLIC Layout



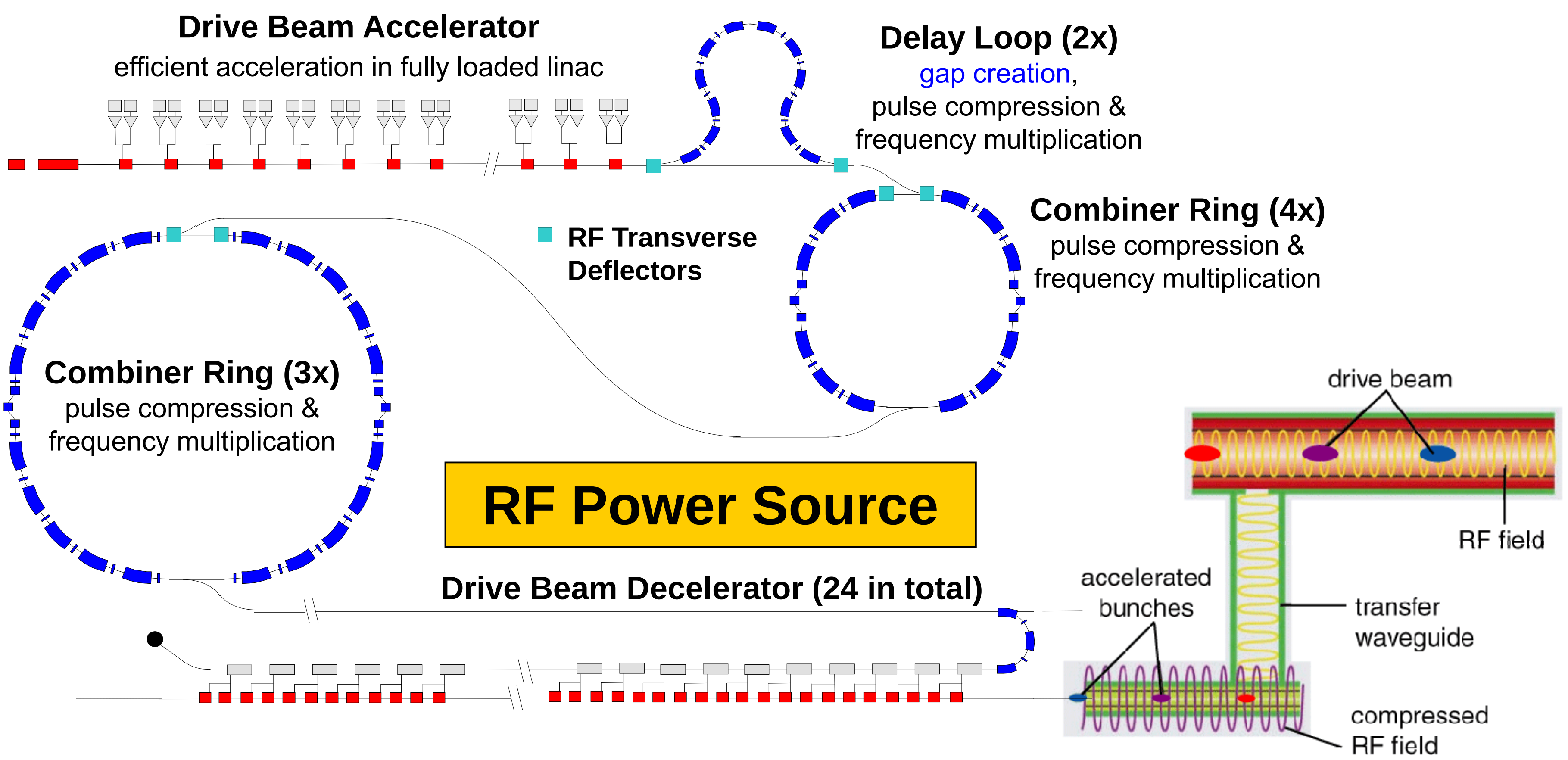
Drive Beam Generation Complex

Drive Beam

Main Beam 3 TeV (CM)

Main Beam Generation Complex

CLIC Two-beam Acceleration Scheme



Drive Beam Accelerator
efficient acceleration in fully loaded linac

Delay Loop (2x)
gap creation,
pulse compression &
frequency multiplication

Combiner Ring (4x)
pulse compression &
frequency multiplication

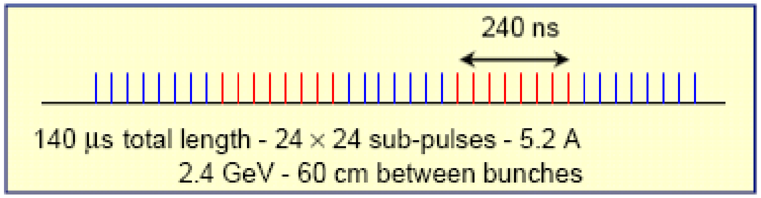
RF Transverse Deflectors

Combiner Ring (3x)
pulse compression &
frequency multiplication

RF Power Source

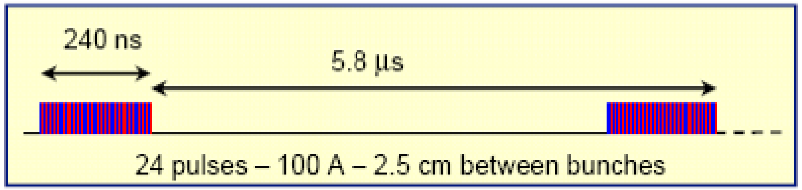
Drive Beam Decelerator (24 in total)

Drive beam time structure - initial



140 µs total length - 24 × 24 sub-pulses - 5.2 A
2.4 GeV - 60 cm between bunches

Drive beam time structure - final



24 pulses – 100 A – 2.5 cm between bunches

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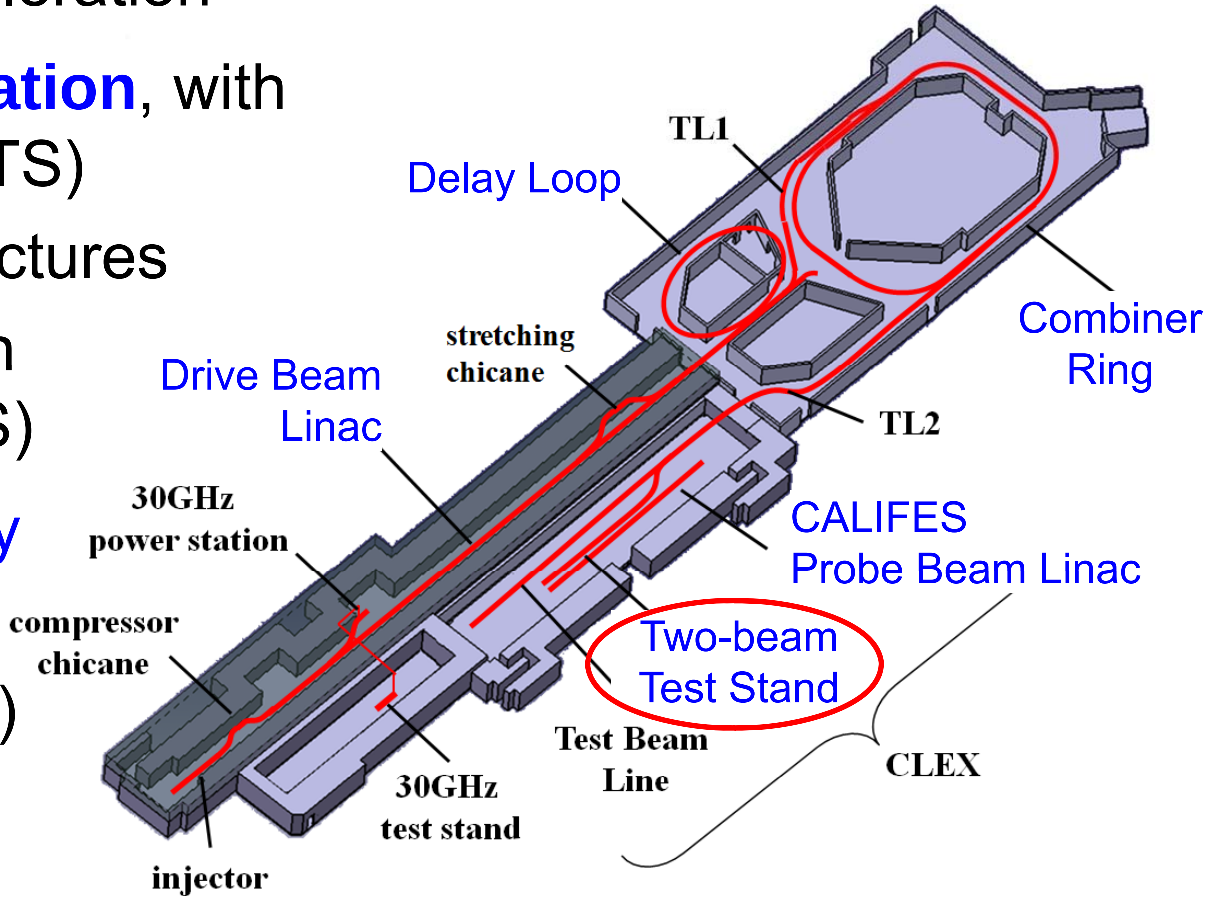
CLIC Test Facility CTF3

- **Drive beam generation**, with
  - appropriate time structure, and
  - fully loaded acceleration
- **Two-beam acceleration**, with CLIC prototype (TBTS)
  - accelerating structures
  - power production structures (PETS)
- Deceleration stability (TBL)
- Photoinjector (PHIN)

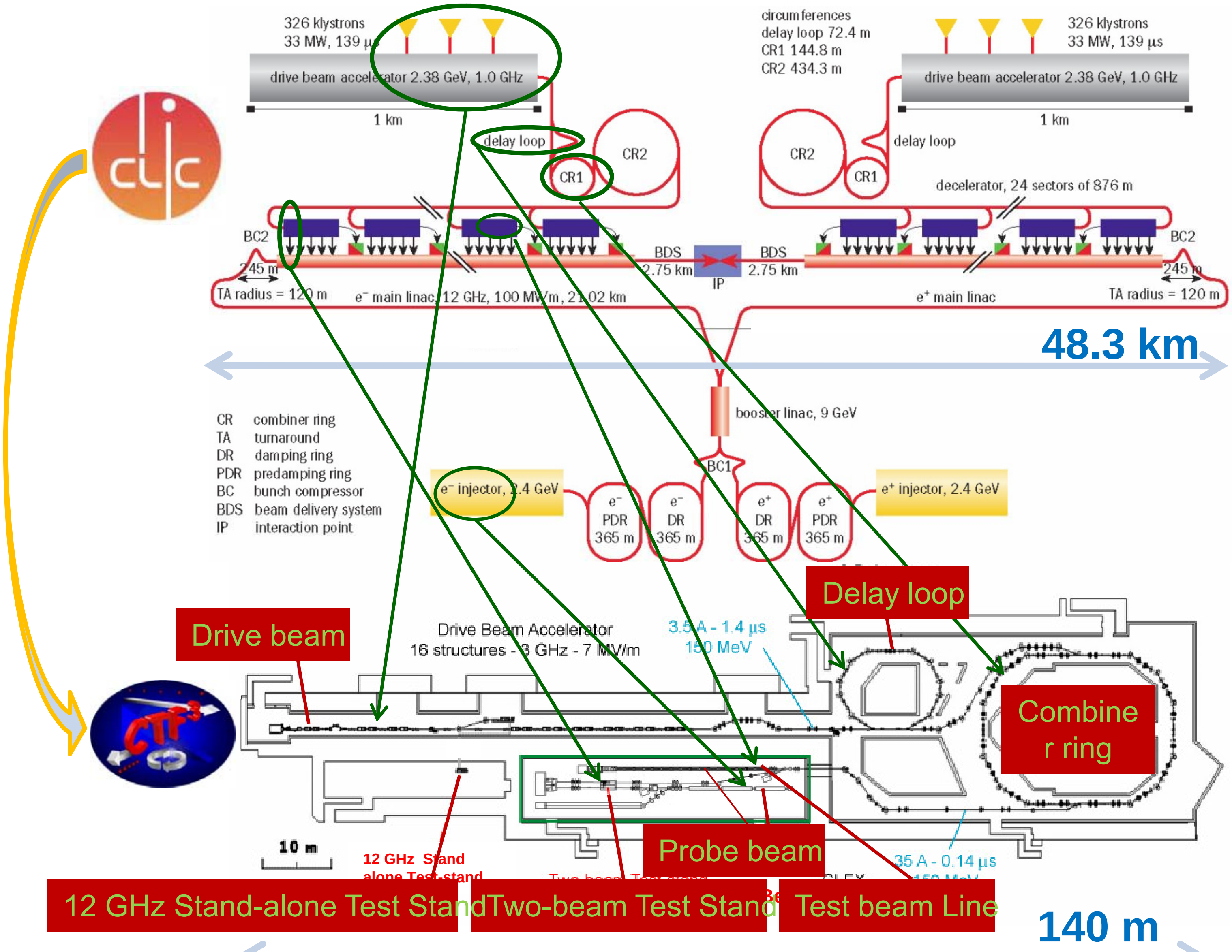


CTF3 Experimental Program

- Two-beam acceleration
  - conditioning and test PETS and accelerating structures
  - breakdown kicks of beam
  - dark (electron) current accompanied by ions
  - install 1, then 3, two-beam modules
- Drive beam generation
  - phase feed forward for phase stability
  - increase to 5 Hz repetition rate
  - coherent diffraction radiation experiments
- Drive beam deceleration
  - extend TBL to 8 then 16 PETS
  - high power production + test stand
- 12GHz klystron powered test stand
  - power testing structures w/o beam
  - significantly higher repetition rate (50 Hz)

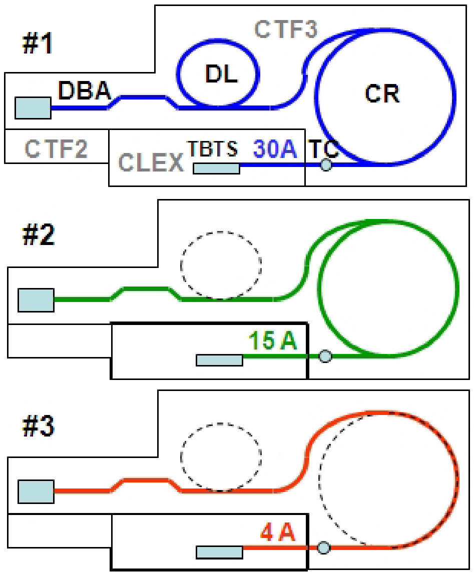
TBTS is the only place available to investigate effects of RF breakdown on the beam

The CTF3 Facility as CLIC Test Bench



CTF3 Drive Beam

- Several operation modes possible,
- Tail clipper (TC) after the CR to adjust the pulse length,
- Upgrade possible to 150 MeV at 5 Hz repetition rate.

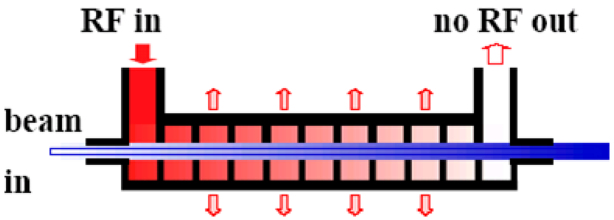


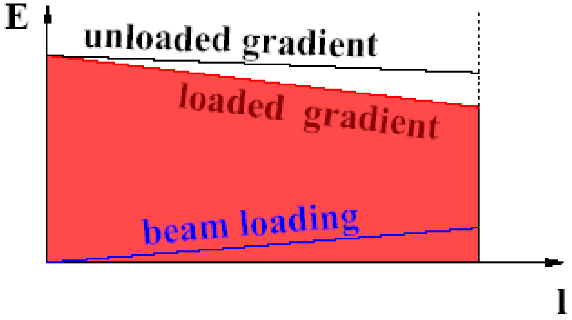
Mode	**#1**	**#2**	**#3**	
Energy	120			[MeV]
Energy spread	2			[%]
Current **(1)**	30	15	4	[A]
Pulse length **(2)**	140	240	1100	[ns]
DBA frequency	1.5	3	3	[GHz]
Bunch frequency	12	12	3	[GHz]
Repetition rate	0.8			[Hz]
PETS power	200	61	5	[MW]

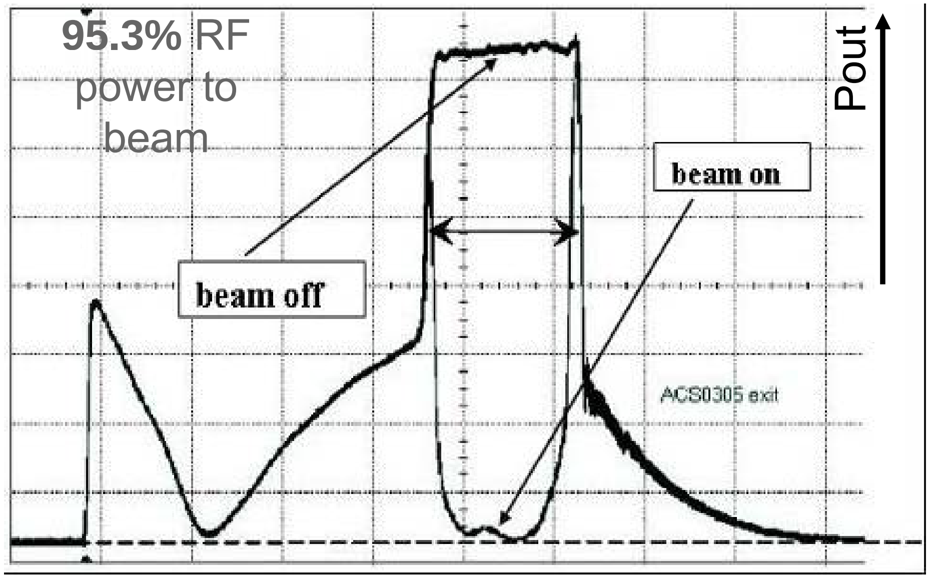
Demonstration Fully Loaded Operation

Efficient power transfer

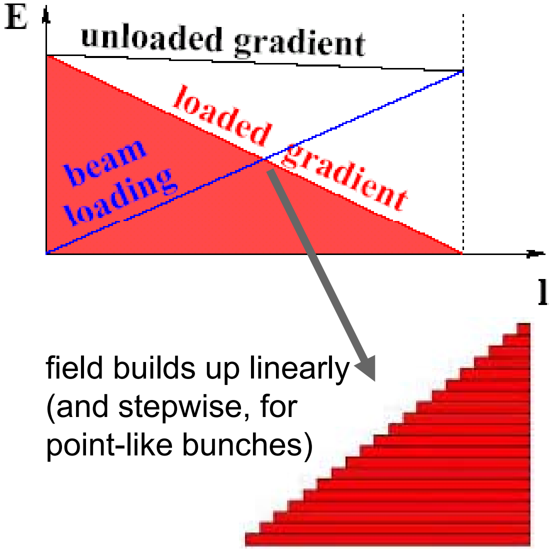
- **“Standard” situation:**
  - small beam loading
  - power at exit lost in load
- **“Efficient” situation:** $V_{ACC} \approx 1/2\ V_{unloaded}$
  - high beam loading
  - no power flows into load





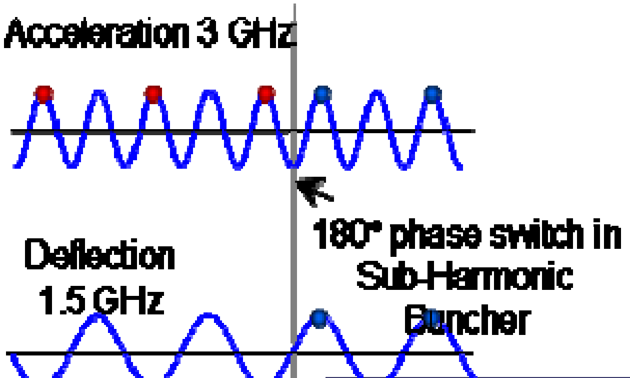


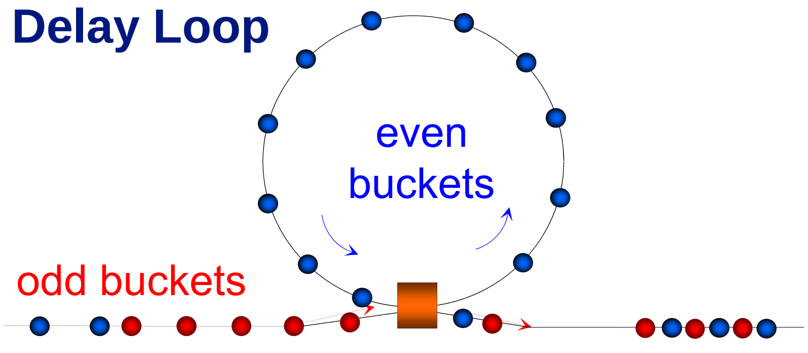
95.3% RF power to beam

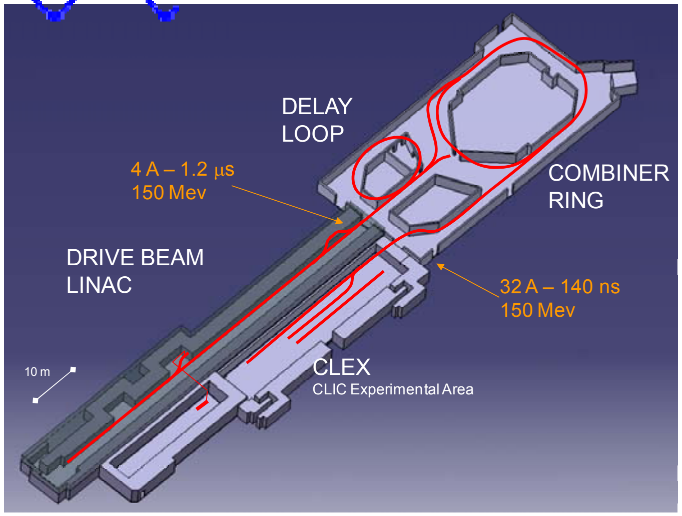


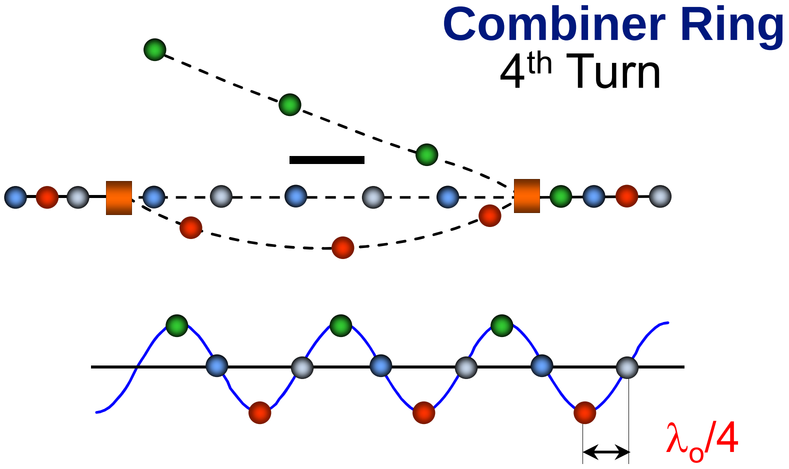
field builds up linearly (and stepwise, for point-like bunches)

Recombination Principle

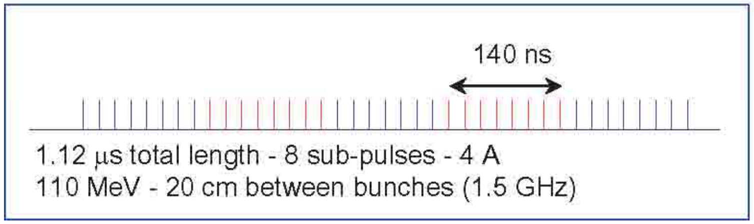






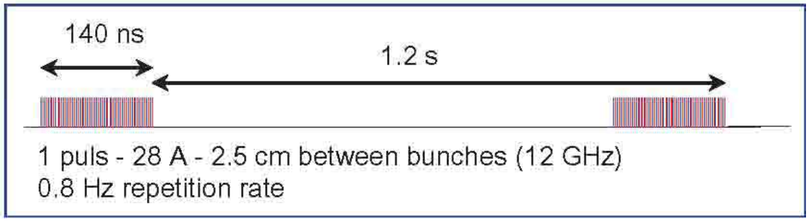


Initial time structure



1.12 µs total length - 8 sub-pulses - 4 A
110 MeV - 20 cm between bunches (1.5 GHz)

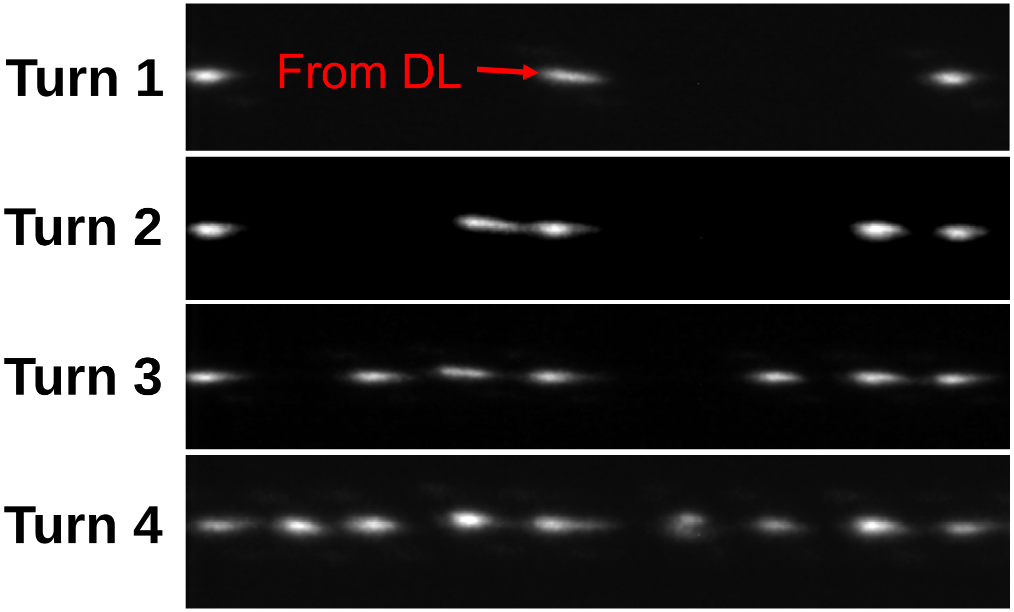
Final time structure



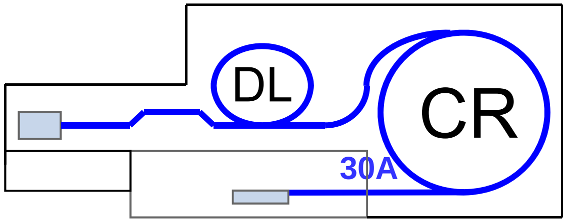
1 puls - 28 A - 2.5 cm between bunches (12 GHz)
0.8 Hz repetition rate

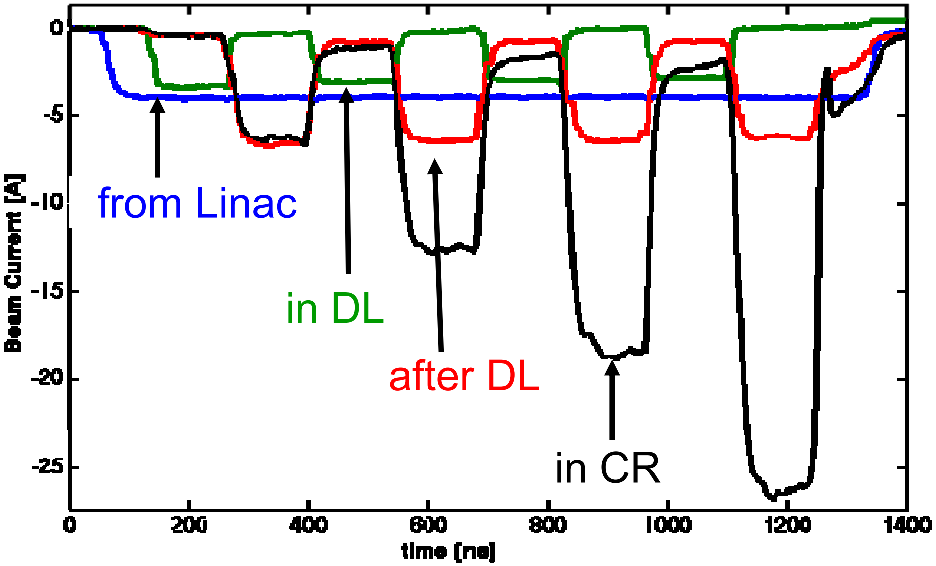
Bunch Re-combination DL + CR

- **Streak camera images from CR**
- bunch spacing:
  - 666 ps initial
  - 83 ps final
- circulation time correction by wiggler adjustment



- **Signal from BPMs**

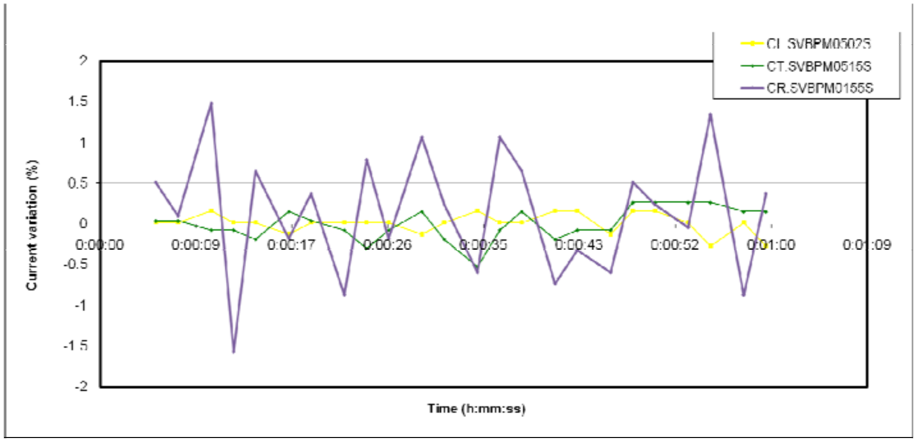




Ongoing Work

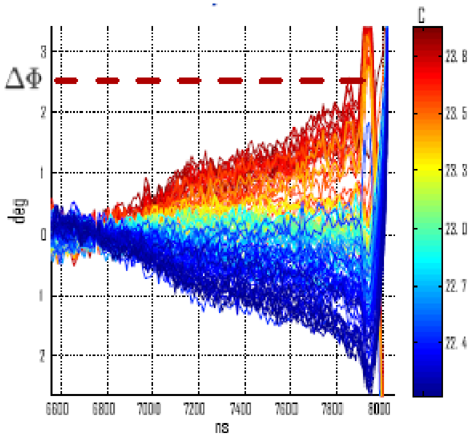
- **Beam current stabilization**
  - CLIC requires stability at 0.075% level
  - ok from linac and DL
    need improvement in CR

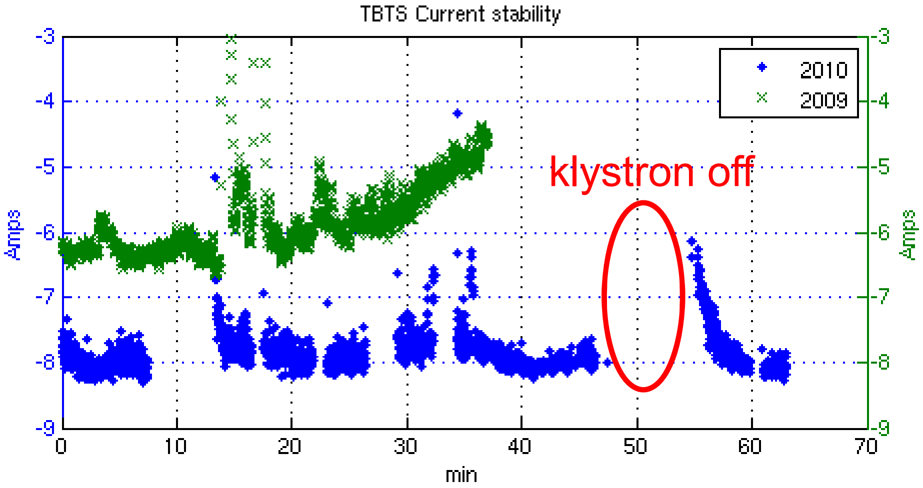
	LINAC	DL	CR
Variation	0.13%	0.20%	1.01%



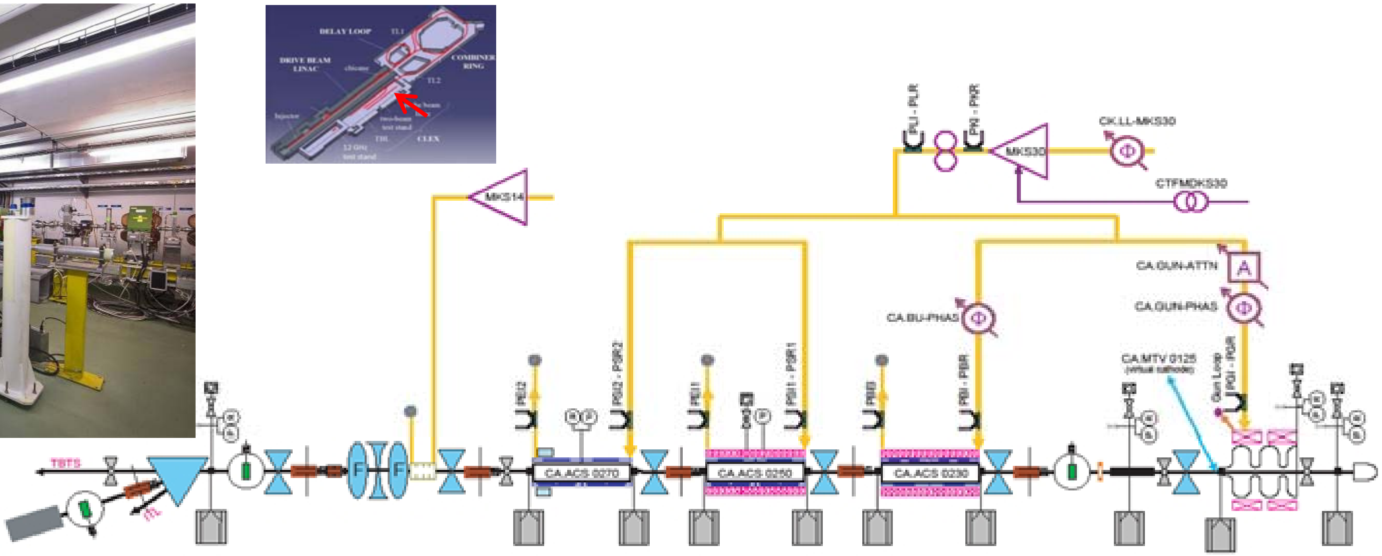
- **Phase stabilization**
  - temperature stabilization
    pulse compressor cavity
- **Transfer line commissioning**
  - transport losses from CR to experiment hall

RF phase stability along pulse (for different ambient temperatures)





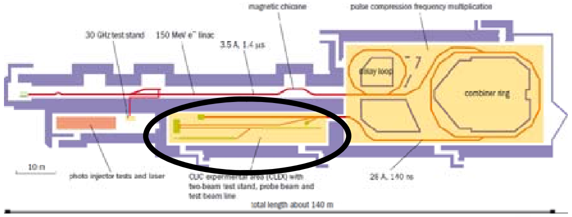
CALIFES Probe Beam

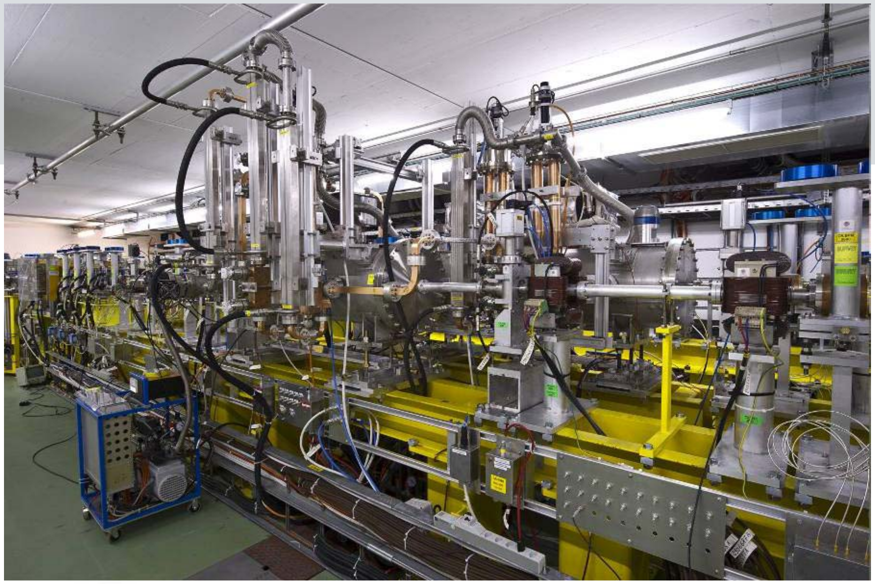


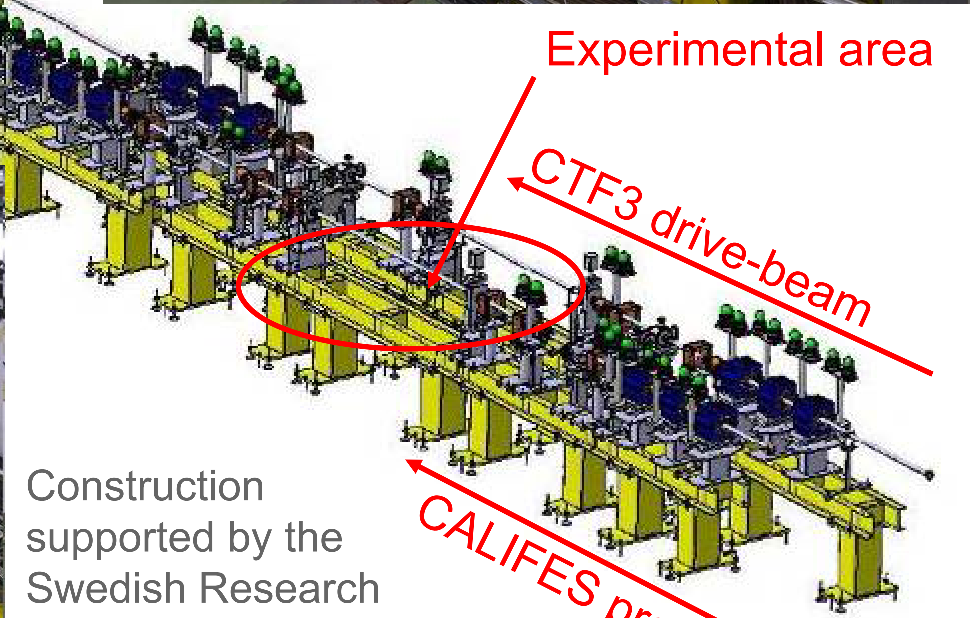
- A standing-wave photo-injector
- 3 travelling-wave structures, the first one used for velocity bunching
- A single klystron (45 MW – 5.5 ms) with pulse compression (120 MW – 1.3 ms)
- A RF network with splitters, phase shifters, attenuator, circulator and couplers

Energy	200 MeV
Energy spread	1% (FWHM)
Pulse length	0.6–150 ns
Bunch frequency	1.5 GHz
Bunch length	1.4 ps
Bunch charge	0.085–0.6 nC
Intensity	
- short pulse	1 A
- long pulse	0.13 A
Repetition rate	0.833 – 5 Hz

Two-beam Test Stand







Spectrometers and beam dumps

Experimental area

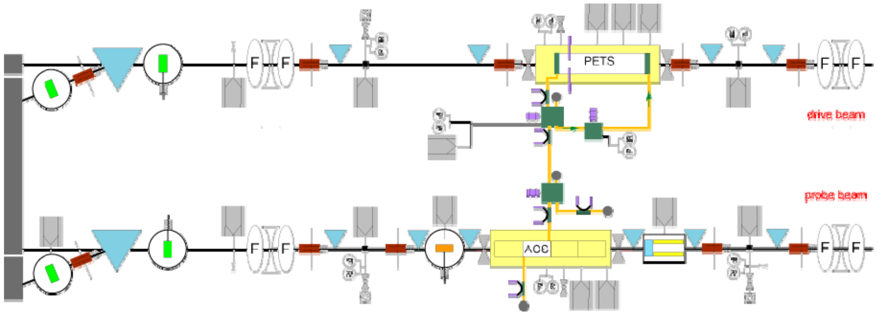
CTF3 drive-beam

CALIFES probe-beam

Construction supported by the Swedish Research Council and the Knut and Alice Wallenberg Foundation

Two-beam Test Stand Prospects

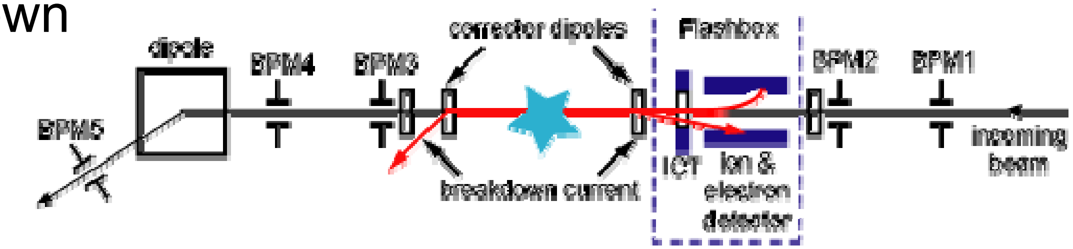
Versatile facility



- two-beam operation
  - 28A drive beam [100A at CLIC]
  - 1A probe beam [like CLIC]
- excellent beam diagnostics, long lever arms
- easy access & flexibility for future upgrades

Unique test possibilities

- power production in prototype CLIC PETS
- two-beam acceleration and full CLIC module
- studies of
  - beam kick & RF breakdown
  - beam dynamics effects
  - beam-based alignment

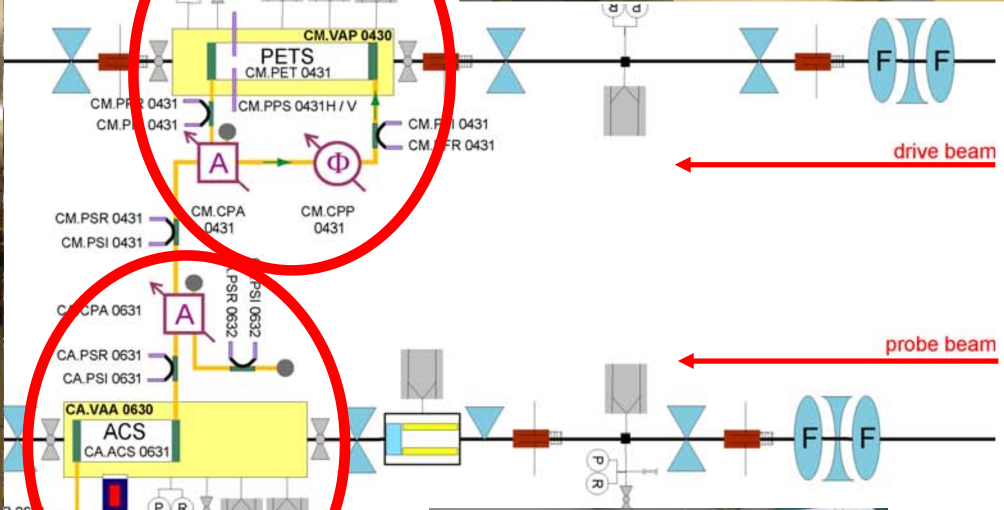


TBTS Test Area

CERN EDMS Id. 894313 (version 6.3)
Roger Ruber, 2010/03/03

11 March 2010

RR201003110009

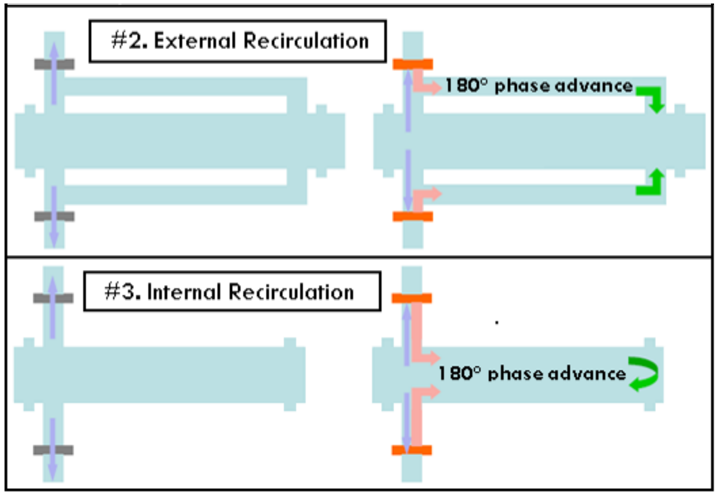


1x PETS
w/ recirculation

1x accelerating
structure

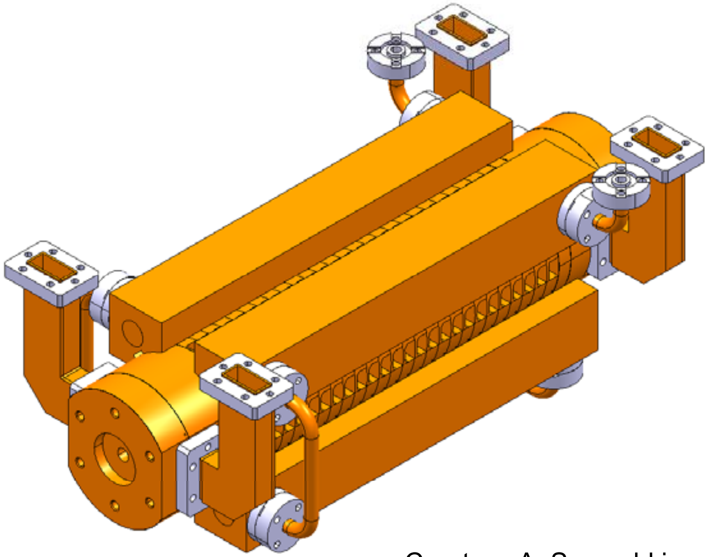
Structures Test Program

- Drive Beam Area
  - Installed:
    - TBTS PETS, 1m long
    - external RF power recirculation
  - Next test foreseen:
    - PETS On/Off option (active reflector)
      A. Cappelletti (04-May-2010)
      4th X-band Workshop
      http://indico.cern.ch/event/75374



Courtesy A. Cappelletti

- Probe Beam Area
  - Installed:
    - TD24 = disks, tapered, damped, 24 cells
      A. Samoshkin (07-Apr-2010)
      CLIC RF struct. dev. meeting
      http://indico.cern.ch/event/72089
  - Next test foreseen:
    - TD24 with wakefield monitor

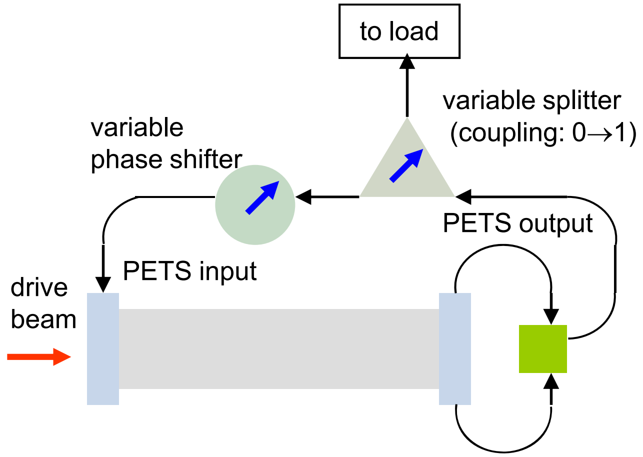


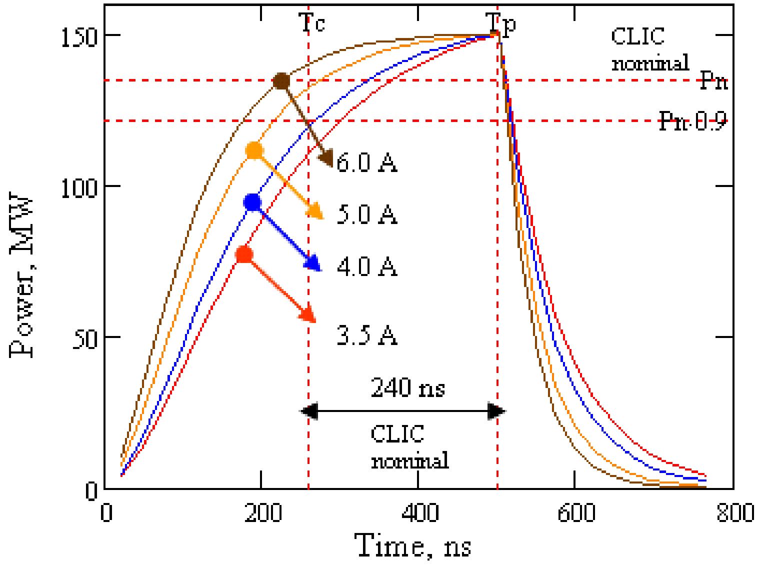
Courtesy A. Samoshkin

PETS Power Recirculation

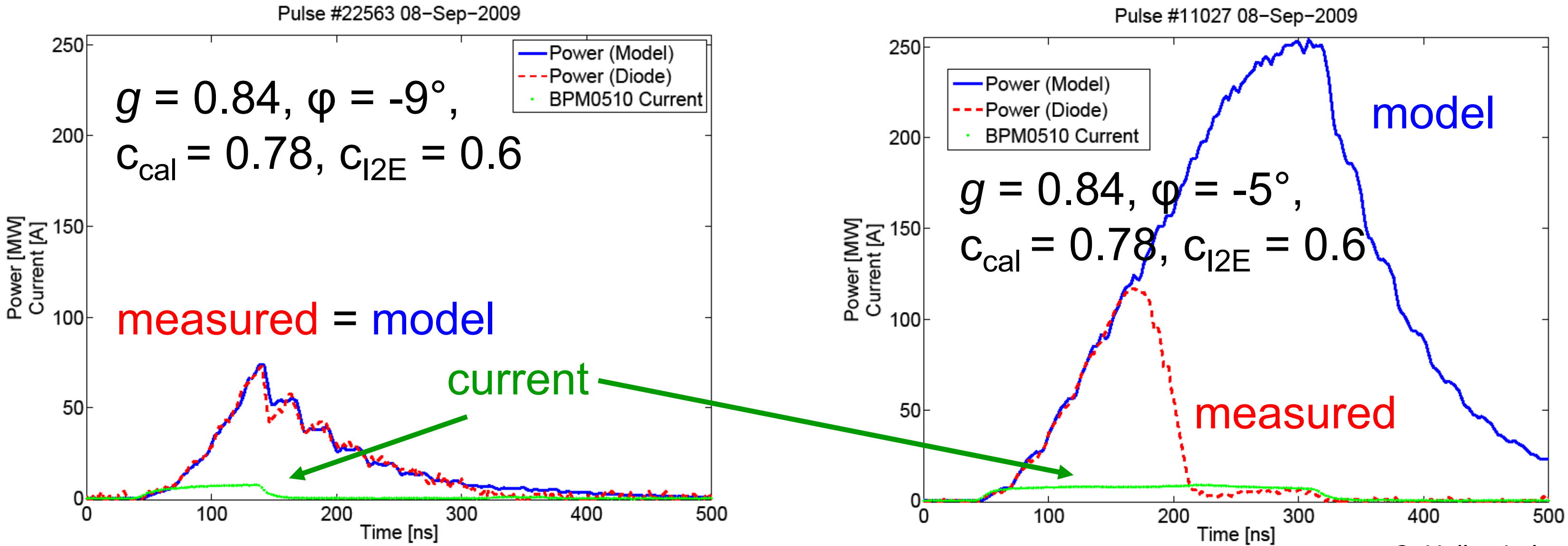
- PETS length 1m, to compensate for lower beam current compared to CLIC
- External recirculation loop
  - increase PETS power in long pulse, low current mode #3
- power recirculation through external feedback loop:
  - electron bunch generates field burst
  - field burst returns after roundtrip time t_r = 26ns

  PETS operates as amplifier (LASER like)
- phase shifter to adjust phase error in the loop





Power Reconstruction with Recirculation



$g = 0.84$, $\varphi = -9°$,
$c_{cal} = 0.78$, $c_{I2E} = 0.6$

measured = model

current

$g = 0.84$, $\varphi = -5°$,
$c_{cal} = 0.78$, $c_{I2E} = 0.6$

model

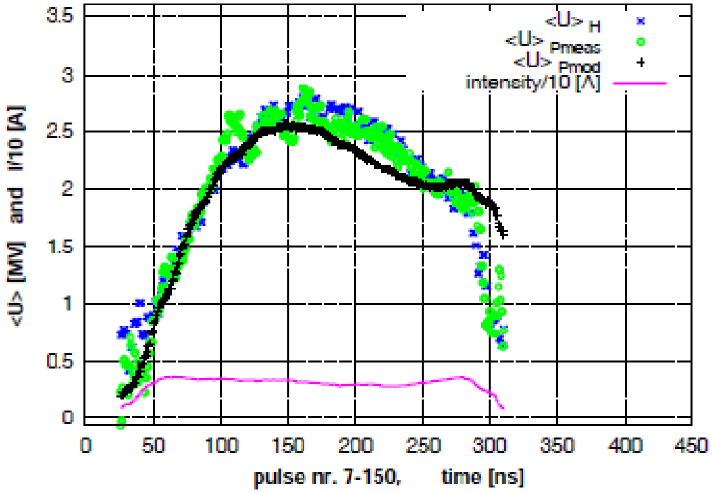
measured

C. Hellenthal,
CLIC Note 811 (2009)

- Parameters constant during normal operation
  → predicts PETS output power (CTF3 Note 092, 094, 096)
- Accurate parameter fit rising slope
  → gives recirculation loop loss factor and phase shift
- Energy difference (ε) measurement and model indicates ”pulse shortening” → breakdown indicator

Drive Beam Energy Loss in PETS

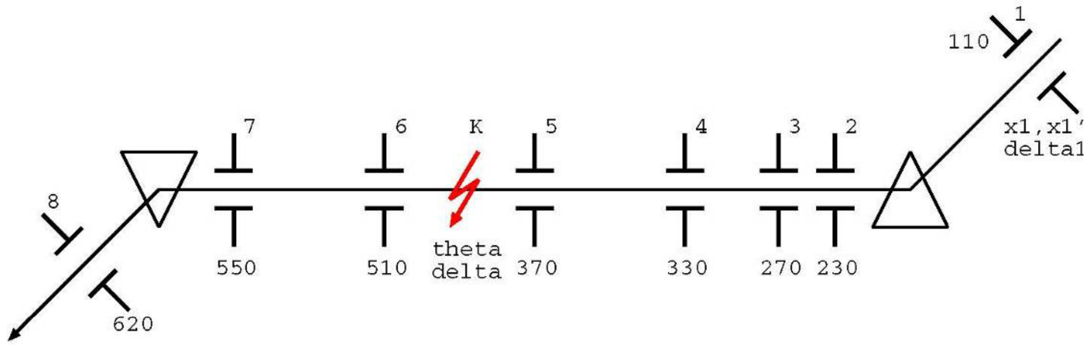
- Energy loss (CTF3 Note 097)
  - spectrometer line (blue)
  - PETS power + BPM intensity (green)
  - BPM intensity (black)
- Include initial energy variation
  → improves kick measurement (CTF3 Note 098)



From E. Adli et al., DIPAC09 MOPD29

$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ R_{11}^{21} & R_{12}^{21} & R_{16}^{21} & 0 & 0 \\ R_{11}^{31} & R_{12}^{31} & R_{16}^{31} & 0 & 0 \\ R_{11}^{41} & R_{12}^{41} & R_{16}^{41} & 0 & 0 \\ R_{11}^{51} & R_{12}^{51} & R_{16}^{51} & 0 & 0 \\ R_{11}^{61} & R_{12}^{61} & R_{16}^{61} & R_{12}^{6K} & 0 \\ R_{11}^{71} & R_{12}^{71} & R_{16}^{71} & R_{12}^{7K} & 0 \\ R_{11}^{81} & R_{12}^{81} & R_{16}^{81} & R_{12}^{8K} & R_{16}^{8K} \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \\ \delta_1 \\ \theta \\ \delta \end{pmatrix}$$

$$\begin{pmatrix} x_1 \\ x_1' \\ \delta_1 \\ \theta \\ \delta \end{pmatrix} - (A^T A)^{-1} A^T \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \end{pmatrix}$$

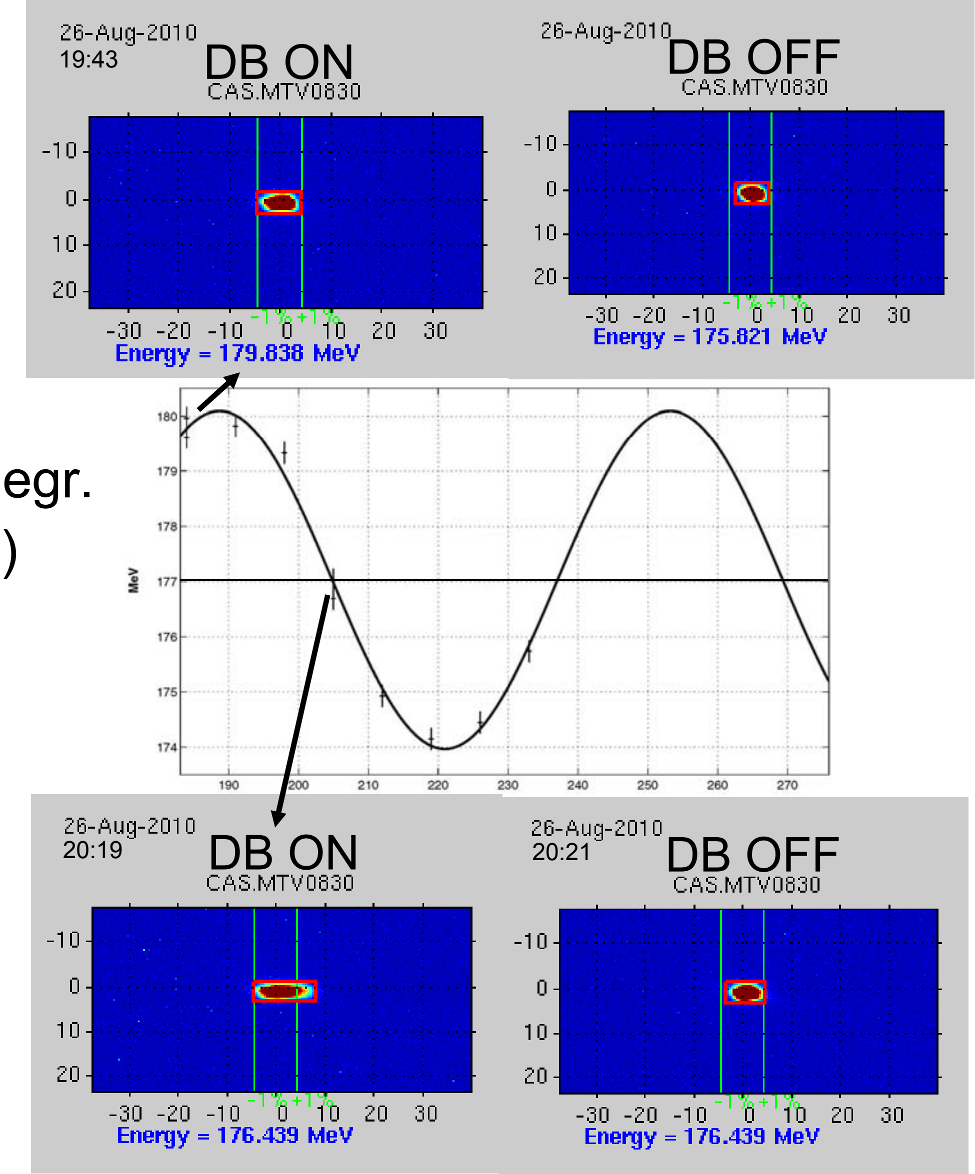


Two-beam Acceleration

- Coarse timing drive and probe beam (ns adjustment)
  - assure signals on BPM and RF channels to overlap
- Calibration of RF system
  - characterize losses in waveguides
    PETS output RF pulse (shape) == ACS output if no probe beam
- Demonstrate acceleration by energy gain probe beam
  - scan along PETS 12GHz RF phase
    (sub-ps timing adjustment, $1^{o} = 0.23$ps):
    modify laser phase to adjust bunches to PETS phase
    → monitor energy gain
  - **Note:** acceleration by 15% → adjust downstream optics!

First Trial Probe Beam Acceleration

- Fine tuning DB↔PB timing
  - **3GHz phase scan klystron**
  - coherent with 1.5GHz laser timing signal
- **~6 MeV peak-to-peak**
  - zero crossing: 177 MeV, 205 degr.
  - phase scaling: 5.58 (expect 4x)
- optimize
  - PB energy spread & bunching
  - klystron pulse compression
  - coherency klystron and laser
  - low input power (ACS not conditioned)



Two-beam Acceleration

- Probe beam repetition rate is twice the drive beam rep-rate,
- DB / PB relative timing and phase adjusted to maximize energy and minimize energy spread after ACS,
- PB pulse length 10 to 100 ns,
- DB pulse length 100 to 240 ns.

Raw video of the spectrum line MTV screen

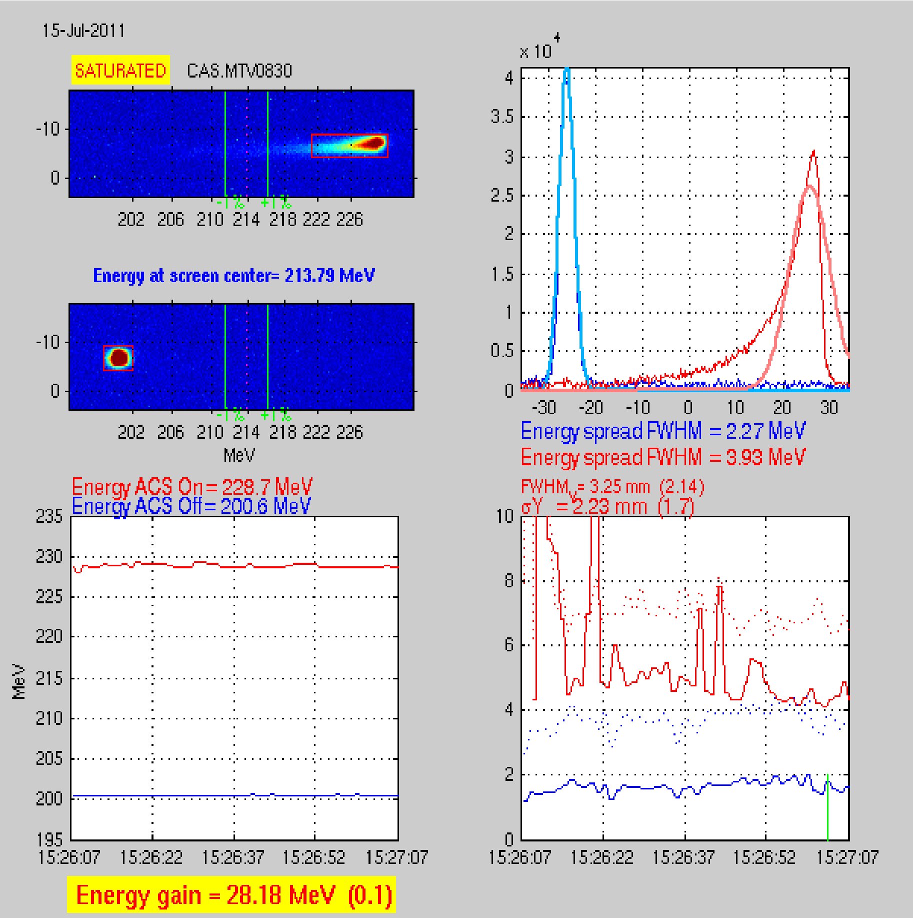
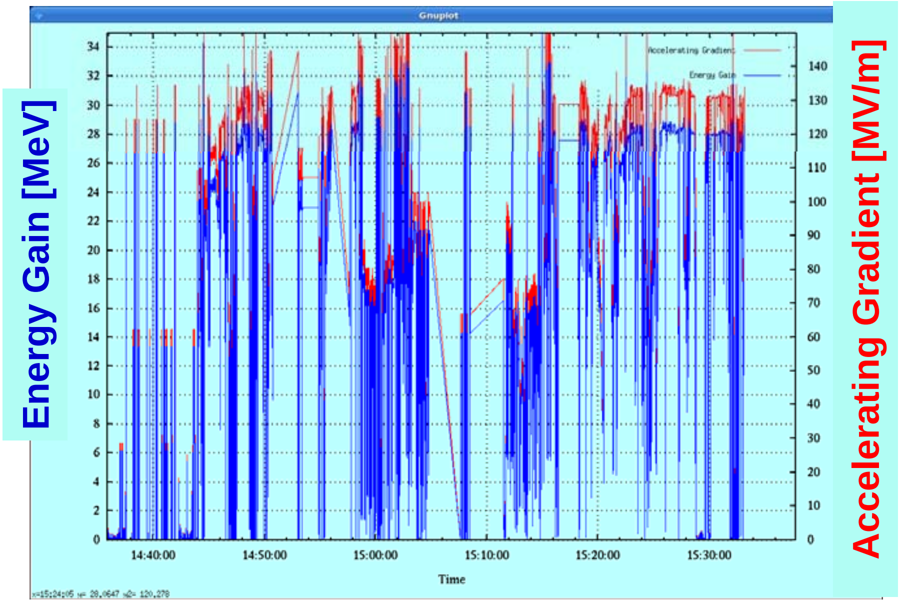


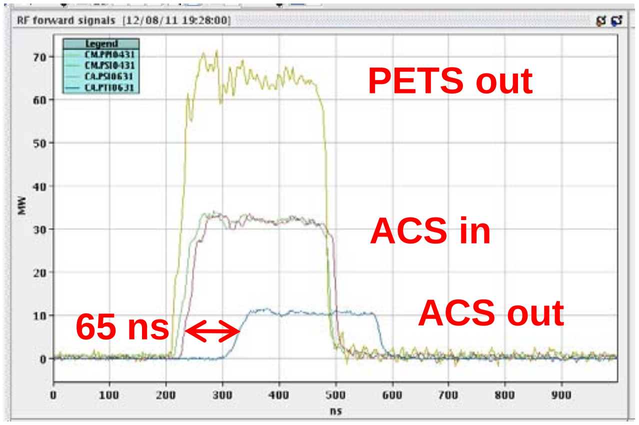
Image processing of the spectrum line MTV screen

Two-beam Acceleration Performance

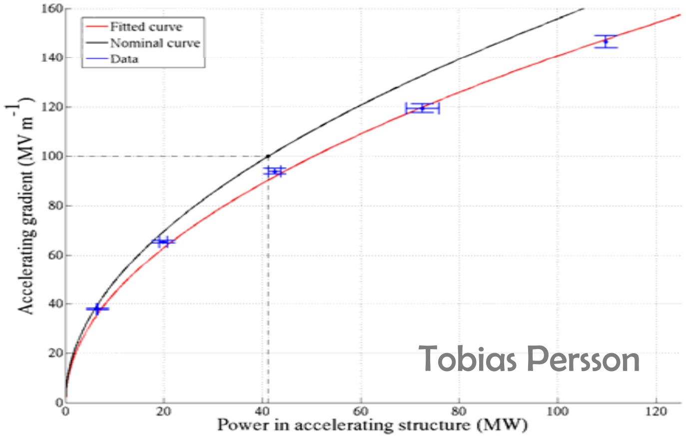


Data logging of energy gain

Javier Barranco



RF power signals



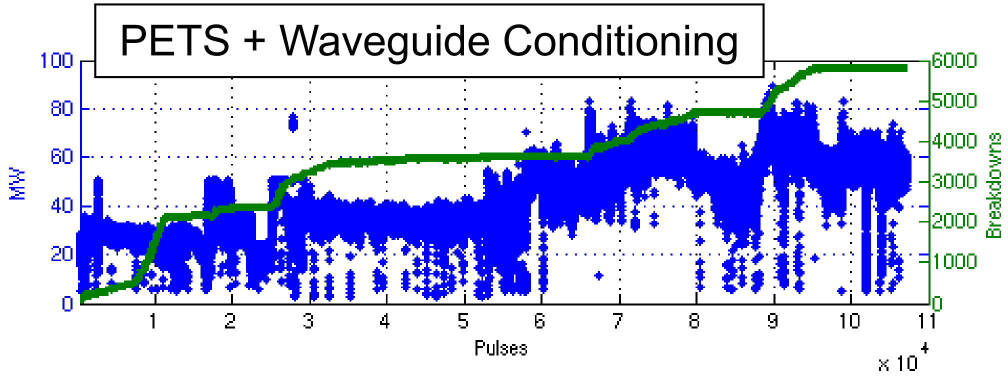
Tobias Persson

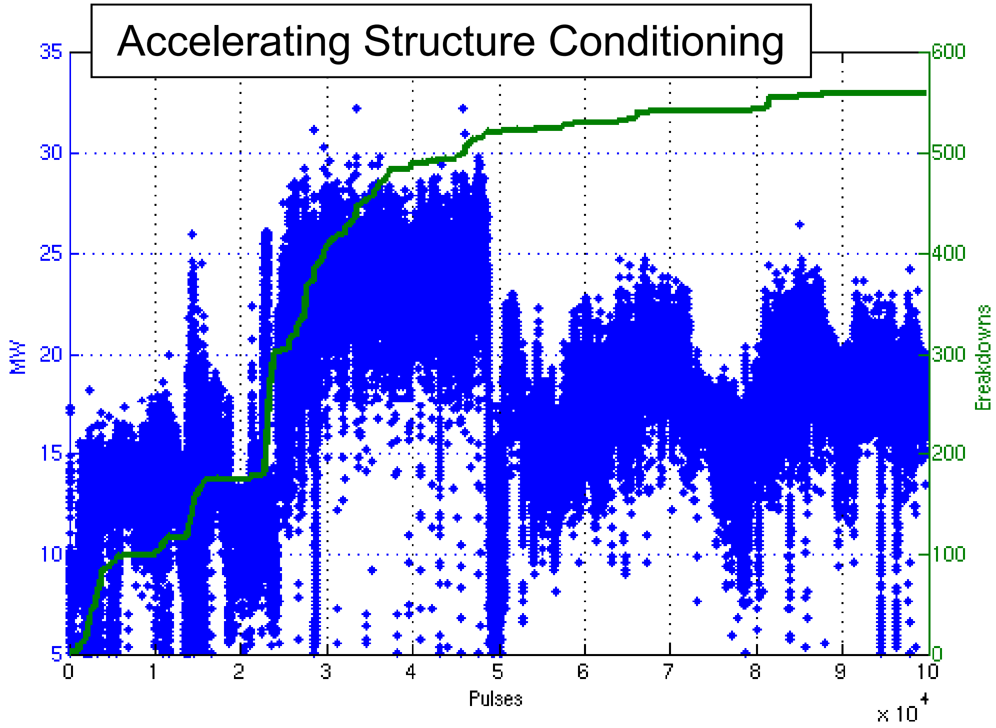
ACS accelerating gradient vs. RF Power in

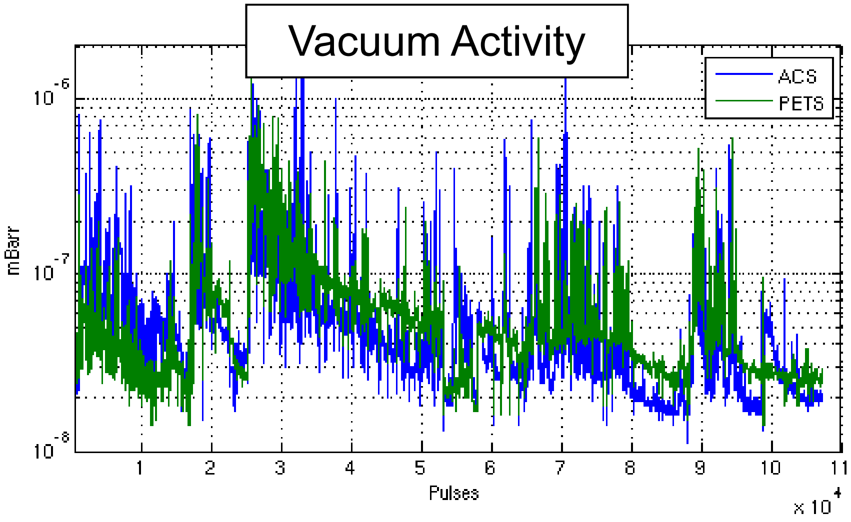
Conditioning Process

Present stable level:

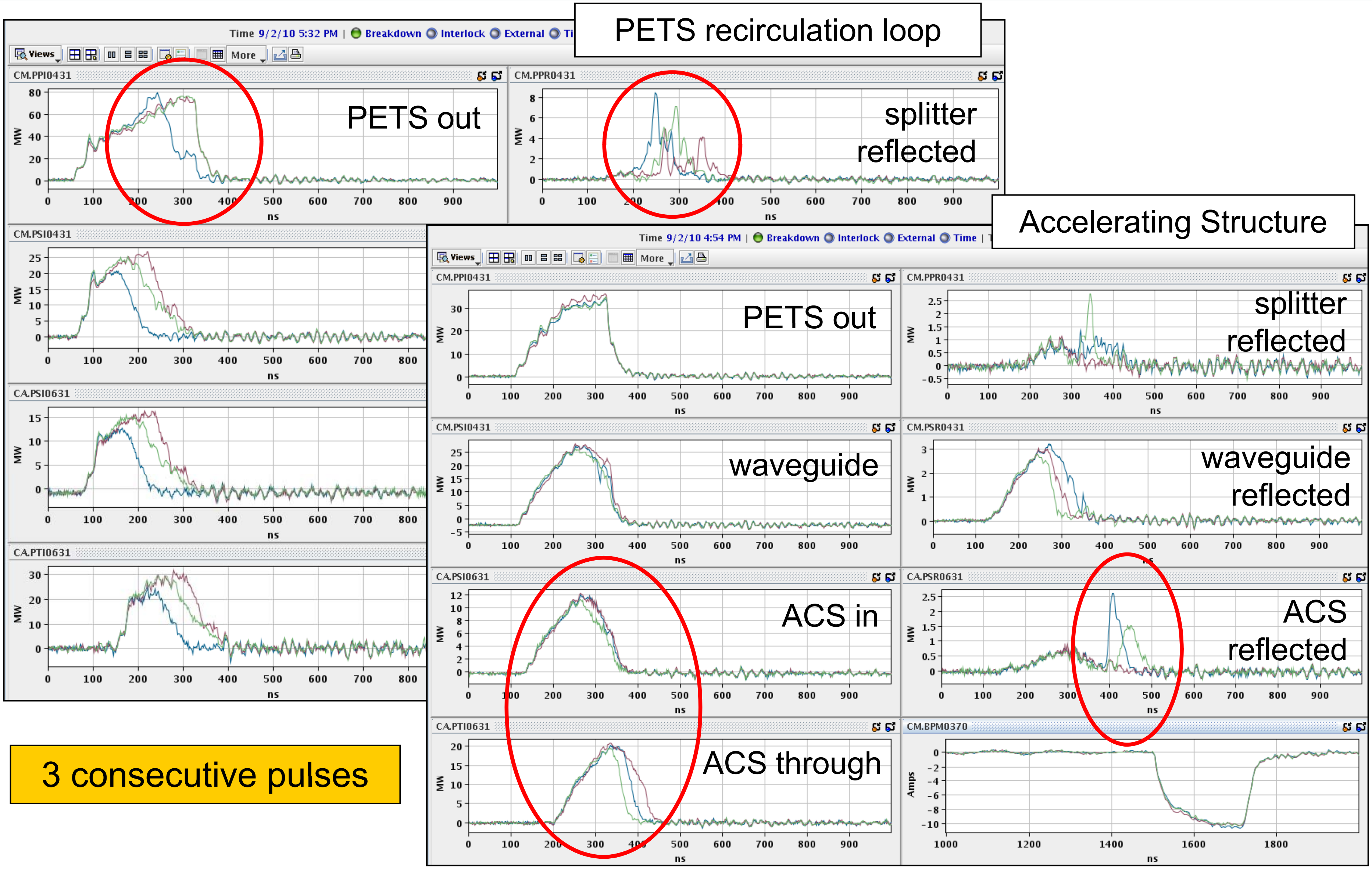
- PETS + recirculation loop
  - ~70 MW peak power,
  - ~200 ns pulse
- Accelerating structure
  - ~23 MW peak power


PETS + Waveguide Conditioning


Accelerating Structure Conditioning


Vacuum Activity

Example RF Breakdowns



PETS recirculation loop

PETS out

splitter reflected

Accelerating Structure

PETS out

splitter reflected

waveguide

waveguide reflected

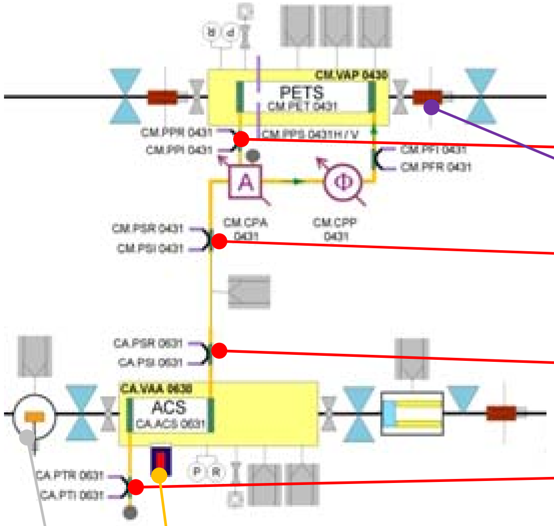
ACS in

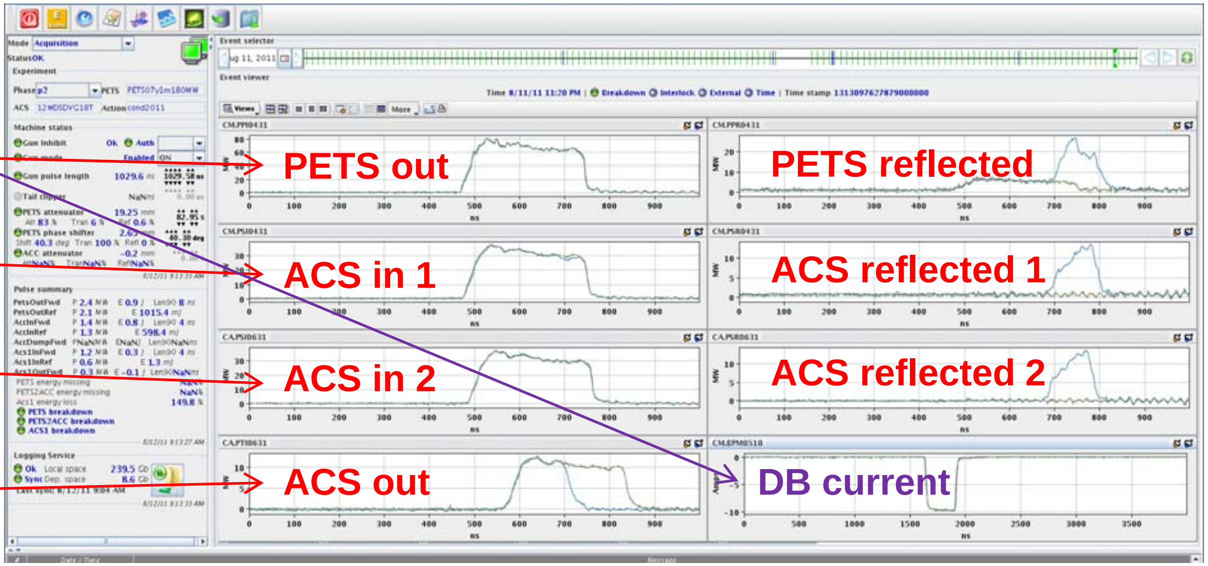
ACS reflected

ACS through

3 consecutive pulses

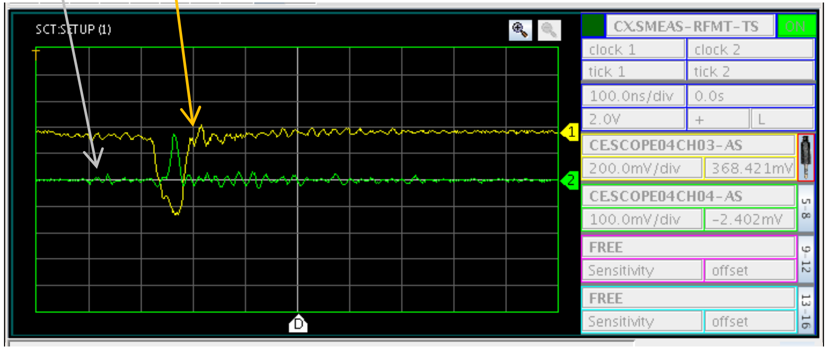
Breakdown Detection





RF power pannel

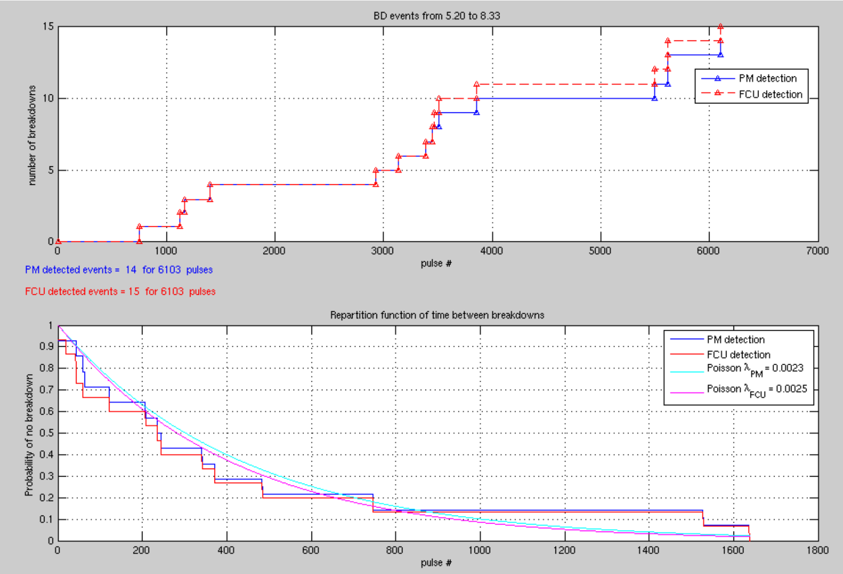
Alexey Dubrowskiy



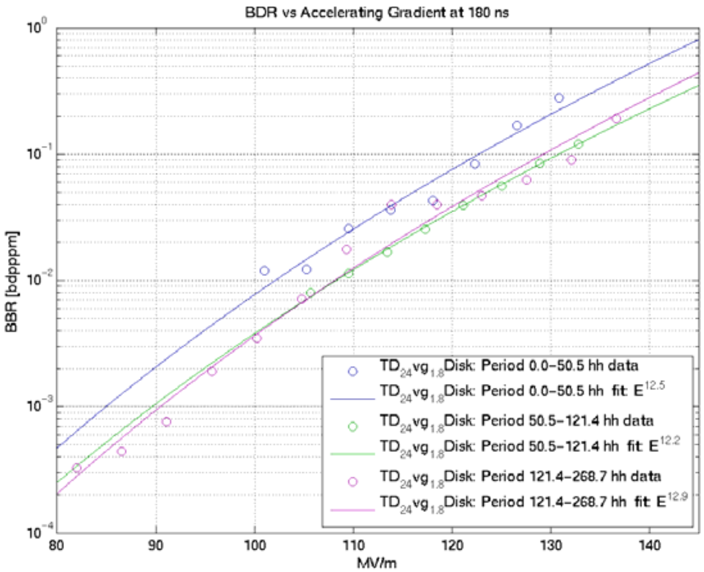
Photomultiplier and Faraday cup signals during BD

- Logical analysis of the RF signals allows to attribute breakdown either to the PETS, to the waveguide network or to the ACS
- PM detection of X-rays and Faraday cup current are typical of ACS breakdowns
- Flash box will allow to analyze electron and ions current produced during breakdown.

Breakdown Rate



ACS breakdown count vs. RF pulse number and repartition law of RF pulse number between BD

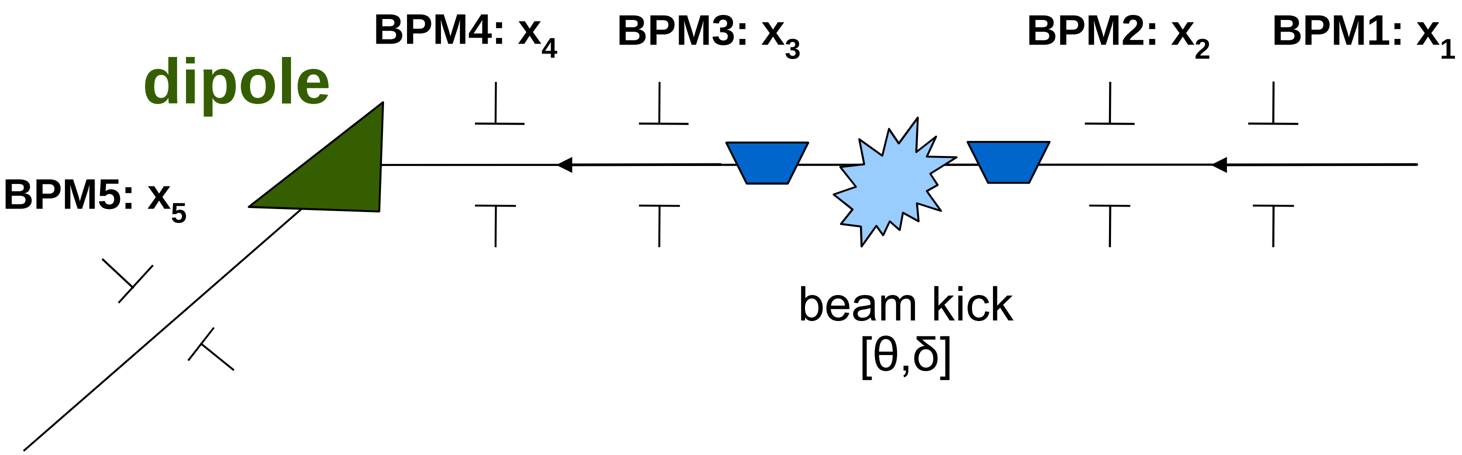


Breakdown rate vs. accelerating gradient for various periods of time.

- During a breakdown, in addition to energy default, the beam is likely to receive a transverse kick,
- It is important for the CLIC design to quantify this effect,
- BPMs are foreseen for this experiment but are presently affected by noise that limits their resolution,
- However kicks effects have been recorded using a beam profile monitor.

Beam Kick Measurements

M. Johnson, CLIC Note 710



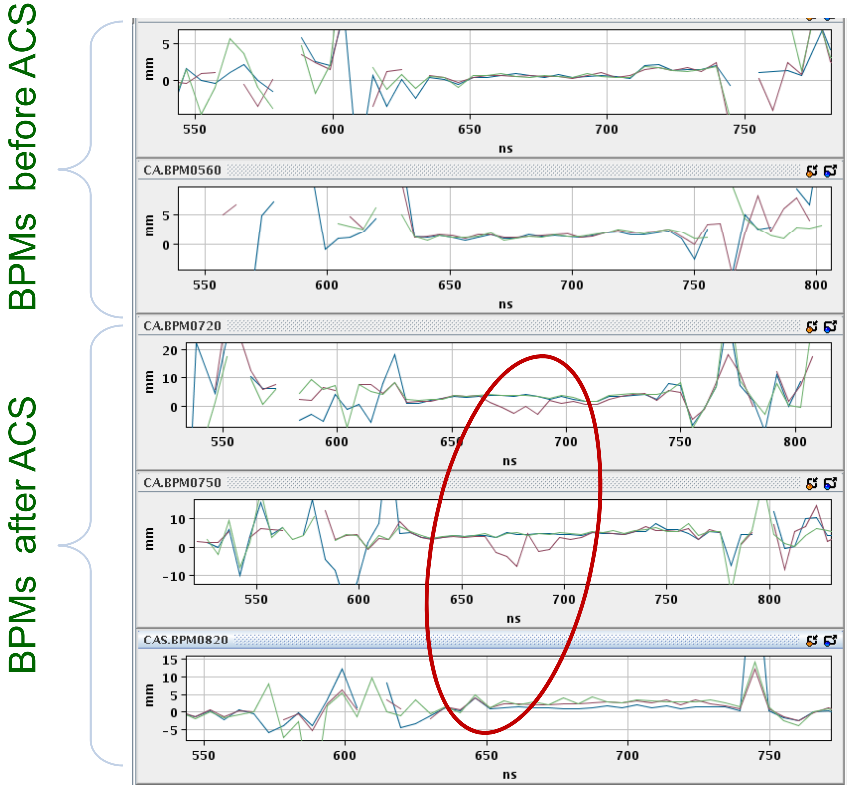
- 5 BPMs: incoming angle & offset, kick angle
- dipole + BPM5 for energy measurement

$$\vec{x} = A\vec{\theta}$$

$$\vec{\theta} = (A^t A)^{-1} A^t \vec{x}$$

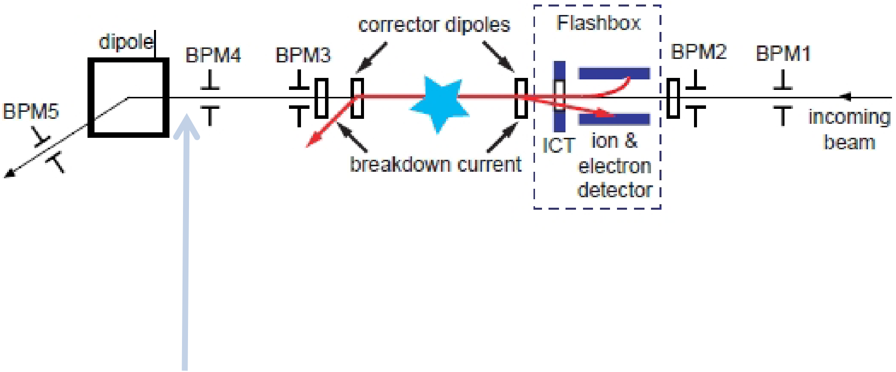
$$\begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ R_{11}^{12} & R_{12}^{12} & 0 & 0 \\ R_{11}^{13} & R_{12}^{13} & R_{12}^{c3} & 0 \\ R_{11}^{14} & R_{12}^{14} & R_{12}^{c4} & 0 \\ R_{11}^{15} & R_{12}^{15} & R_{12}^{c5} & D^5 \end{pmatrix} \begin{pmatrix} x_1 \\ x_1' \\ \theta \\ dp/p \end{pmatrix}$$

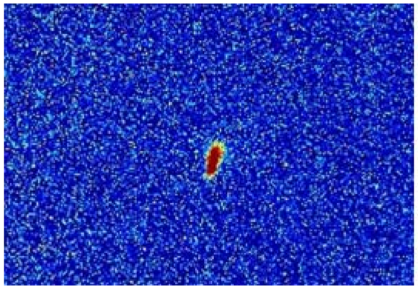
Breakdown Kick



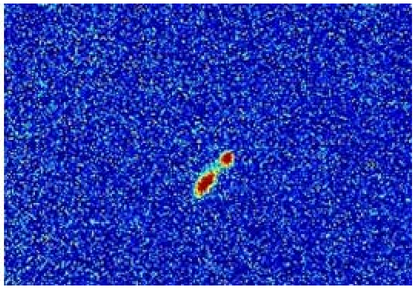
Volker Ziemann

Possible kick recorded during a breakdown





Beam without BD

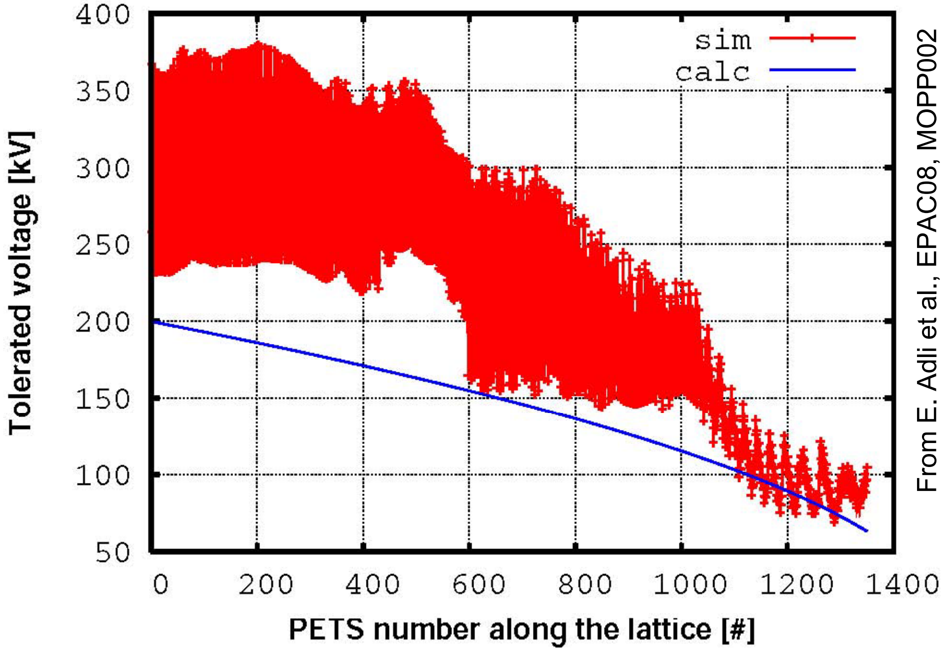


Andrea Palaia

Beam with BD
Kick : 0.2 mrad

- Present BPM noise level too high,
- Measurements with MTV screen instead.

Importance of the Drive Beam Kick



From E. Adli et al., EPAC08, MOPP002

- Maximum accepted PETS break down voltage in CLIC
  - transverse voltage required for 1mm offset in drive beam
  - as function of PETS (position) along linac
- PETS beam kick estimate: (point like bunch, 15GHz)

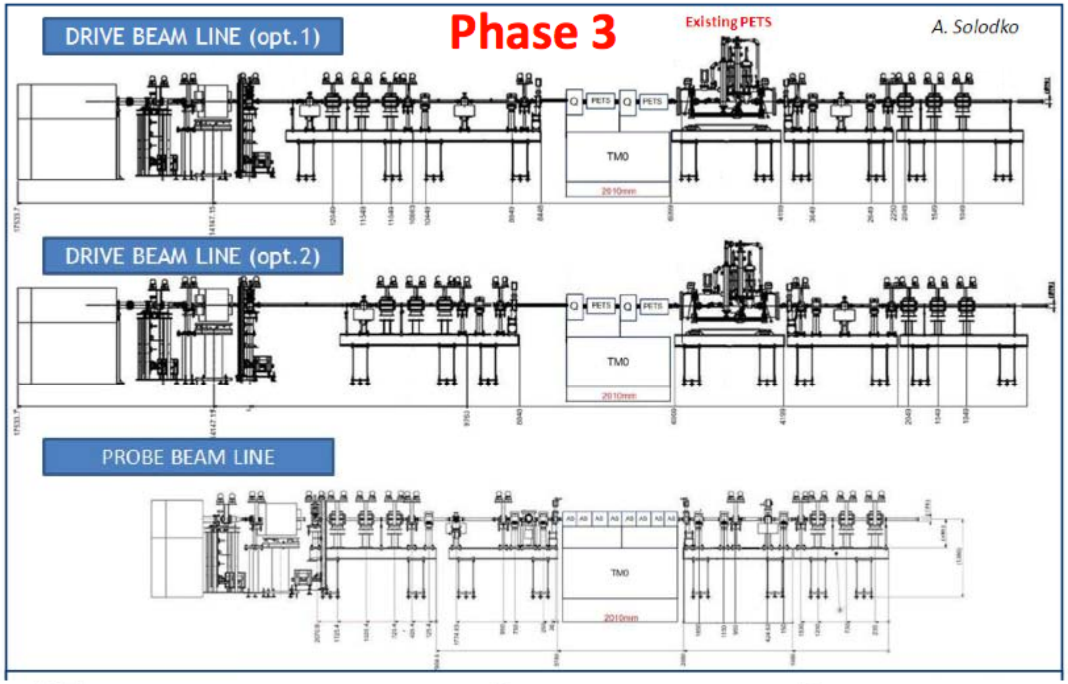
$$\theta/x_P = 2\frac{L_{\mathrm{PETS}}}{E_{tot}} e \frac{I}{f_{\mathrm{bunch}}} k'_T = 27\mu\mathrm{rad/mm}$$

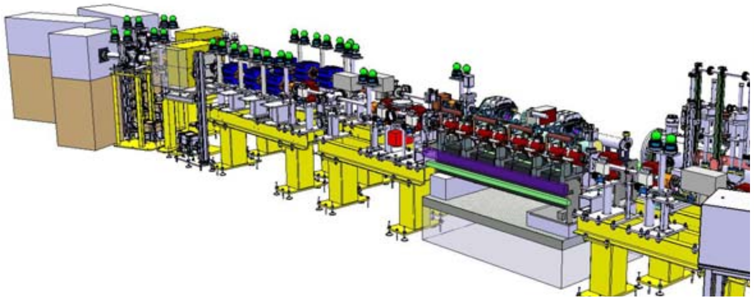
From E. Adli, Thesis (2009)

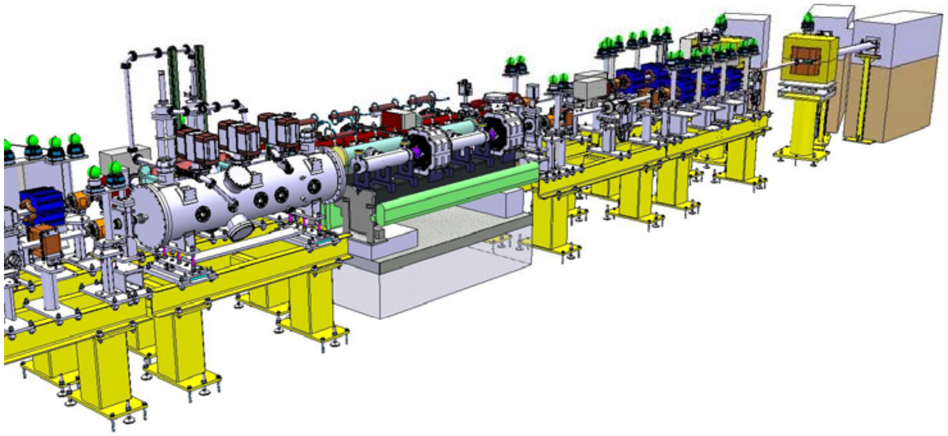
TBTS Phase 3: One Test Module

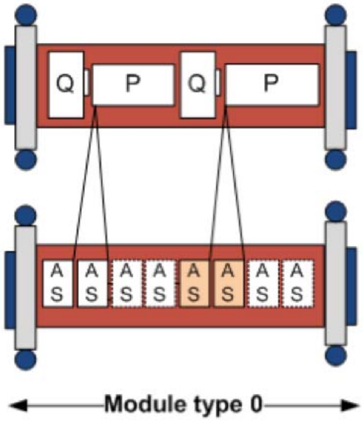
- Module type 0
  - double length PETS
  - 8 ACS (4 powered)

germana.riddone@cern.ch





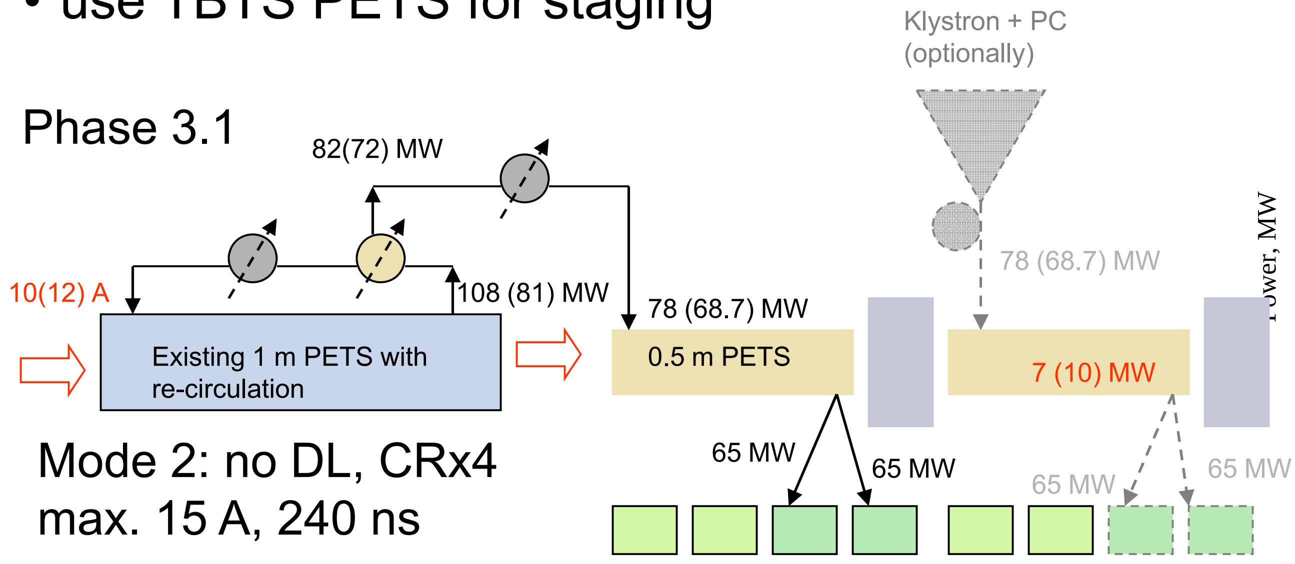




TBTS Phase 3 Powering Schemes

- double length PETS at 30 A, barely 65 MW
- use TBTS PETS for staging

Phase 3.1



Klystron + PC (optionally)

82(72) MW

10(12) A

108 (81) MW

78 (68.7) MW

78 (68.7) MW

Existing 1 m PETS with re-circulation

0.5 m PETS

7 (10) MW

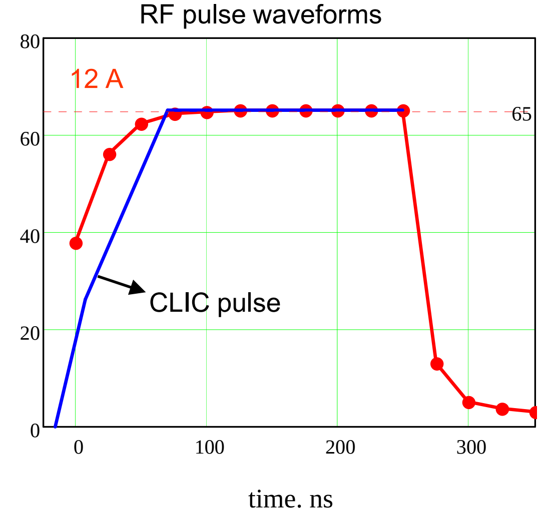
65 MW

65 MW

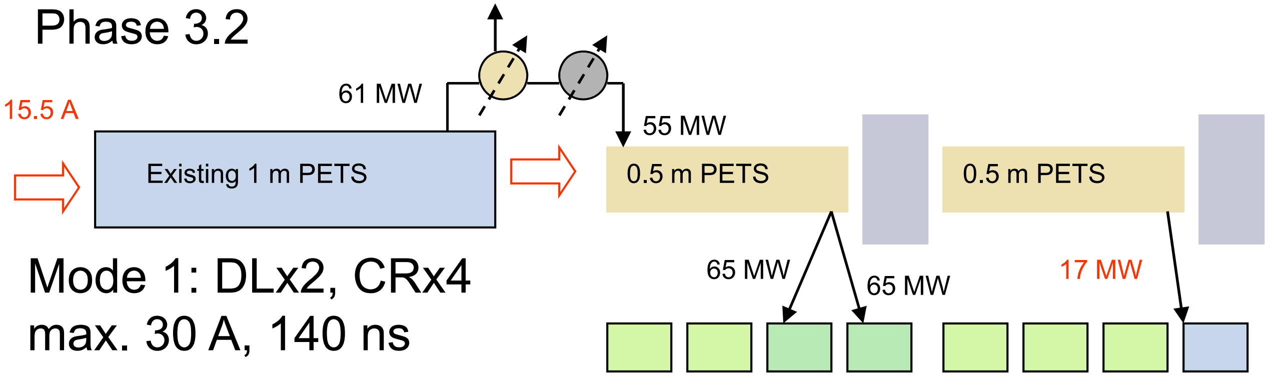
65 MW

65 MW

Mode 2: no DL, CRx4
max. 15 A, 240 ns



Phase 3.2



61 MW

15.5 A

55 MW

Existing 1 m PETS

0.5 m PETS

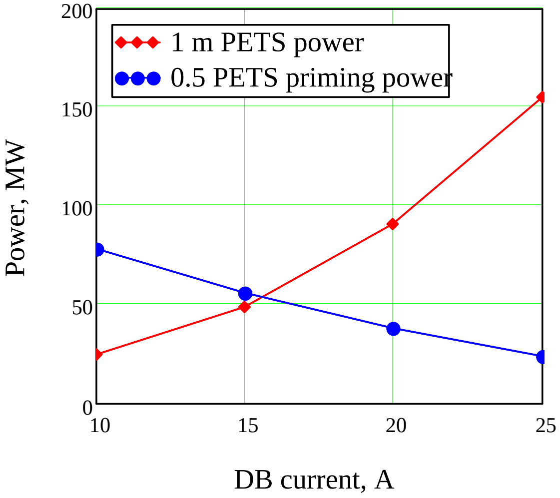
0.5 m PETS

65 MW

65 MW

17 MW

Mode 1: DLx2, CRx4
max. 30 A, 140 ns



Conclusions

- Reached first milestones:
  - Drive beam generation with appropriate time structure and fully loaded acceleration.
  - Two-beam acceleration with CLIC prototype structures.
- Continued operation:
  - Optimize beam and two-beam acceleration.
  - Investigate RF breakdown effects on beam.
- Planned enhancements:
  - 12 GHz klystron powered test stand
  - Install full two-beam test modules.

Many thanks to all colleagues, their work and their suggestions!