Course B: rf technology
Normal conducting rf
Part 3: Linear Collider Hardware

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Seventh International Accelerator School for Linear Colliders
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We will now step back from theory and have a look at specific CLIC hardware.

We have already covered a lot of the theory although there is some more to come.

Still it is a good moment to look at real objects to give a context for all the abstract ideas that you have been seeing.

We will cover:

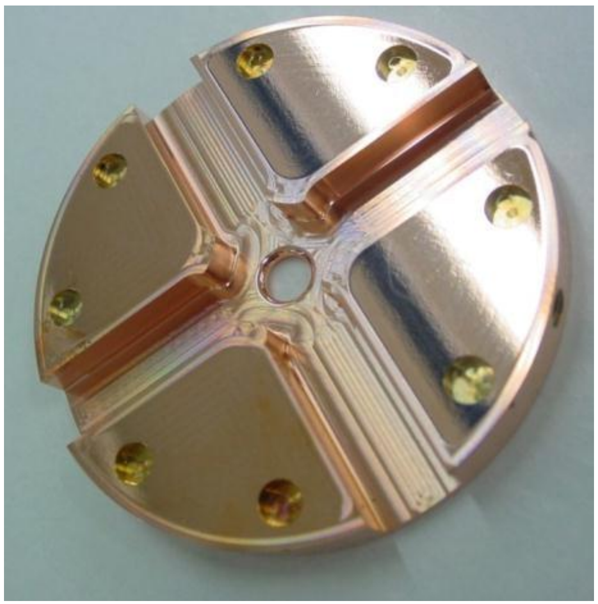
1. Accelerating structures
2. Two-beam concept
3. PETS (power generating) structures
4. A little bit about alignment and stabilization

This section will be basically a seminar on the CLIC rf system.

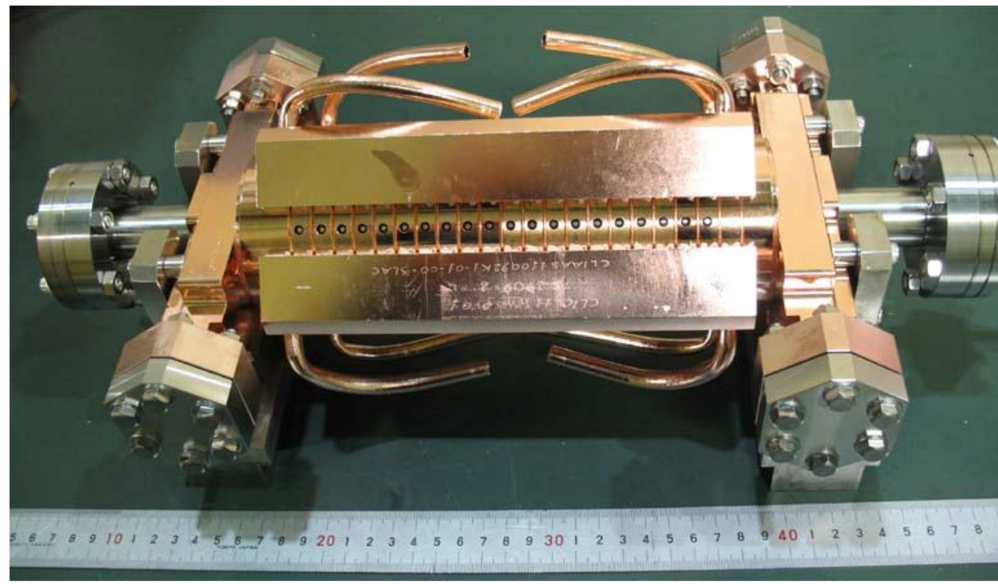
The CLIC accelerating structure

Now that you have a feeling for the basic mechanisms which underlie high-efficiency acceleration, we will look into the main features of the CLIC rf system.

Let's start by looking at the CLIC accelerating structure:



The basic component: diamond turned and milled disk. We form a periodic structure by stacking them. The radial lines are damping waveguides



An assembled high-power test structure. Made in a collaboration between CERN, KEK and SLAC.

Accelerating structure specs.

High-gradient:

1. 100 MV/m loaded gradient
2. 156 (flat top)/240 (full) ns pulse length
3. Less than 3×10^{-7} breakdowns/pulse/m

we observe the interrelation

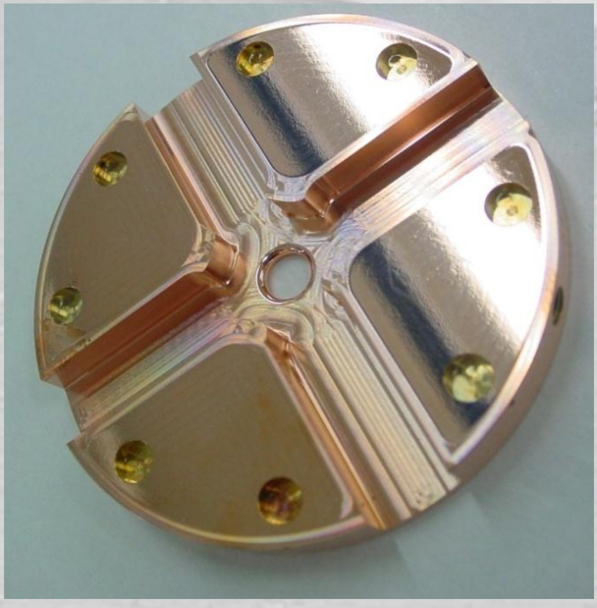
$$BDR \propto E^{30} \tau^{5}$$

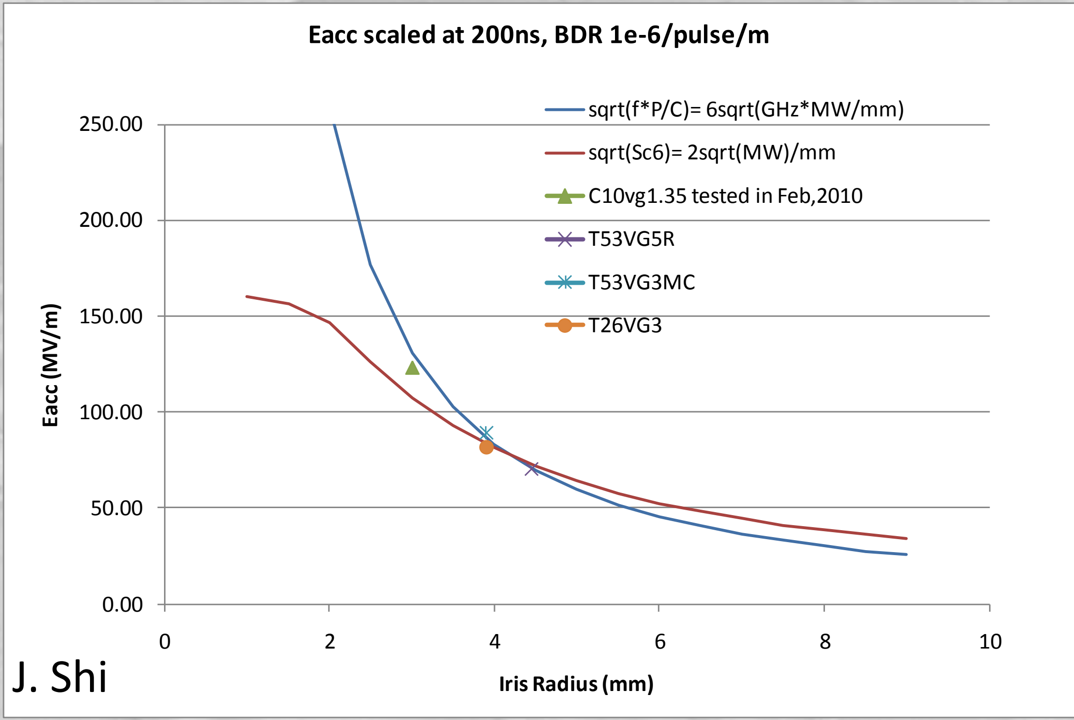
Accelerating structure specs

Beam dynamics:

1. 5.8 mm diameter minimum average aperture (short range transverse wake)
2. < 1 V/pC/mm/m long-range transverse wakefield at second bunch (approximately x50 suppression).

$$W_t \propto a^3$$ but





J. Shi

Accelerating structure characteristics

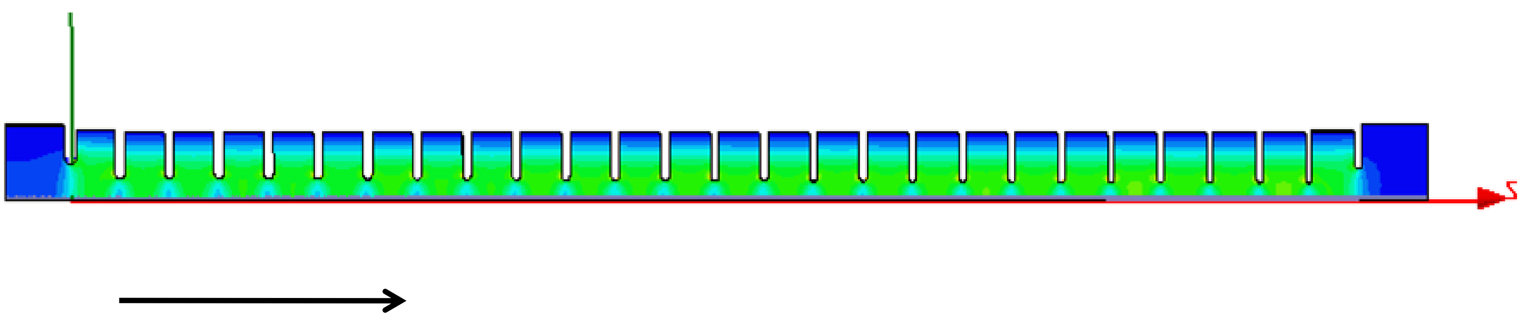
Operating frequency: 11.994 GHz → λ free space is 25 mm

Operating phase advance: $2\pi/3$

Number of cells: 26+2

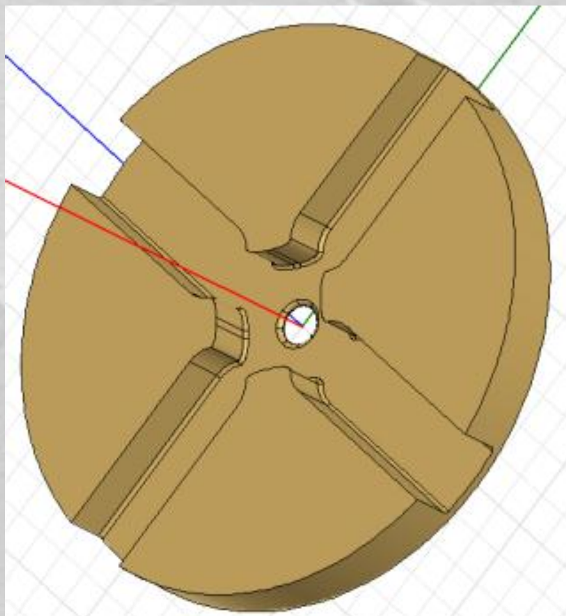
→ Active length: 230 mm

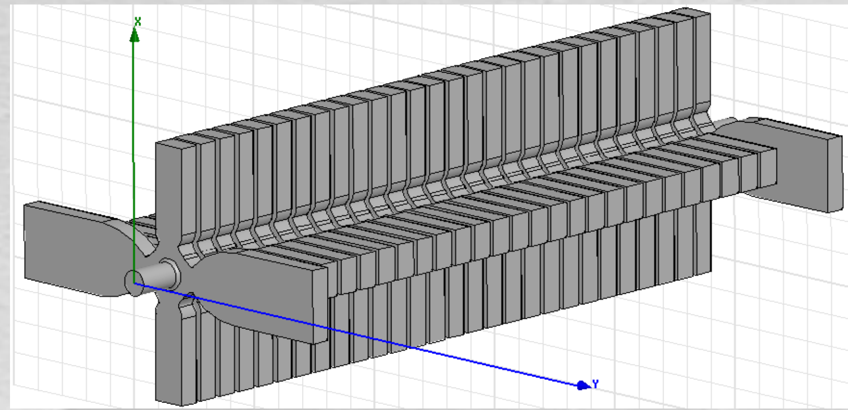
CLIC structures are tapered, for reasons of high-gradient performance and wakefield suppression which we will discuss later.



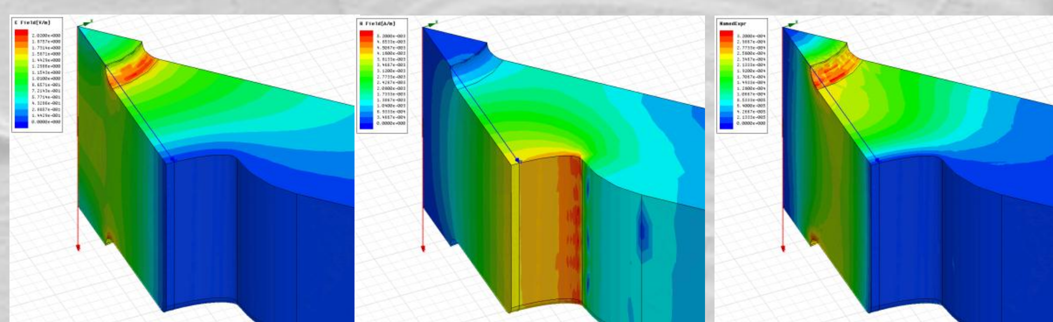
Power flow and beam direction

Accelerating structure features

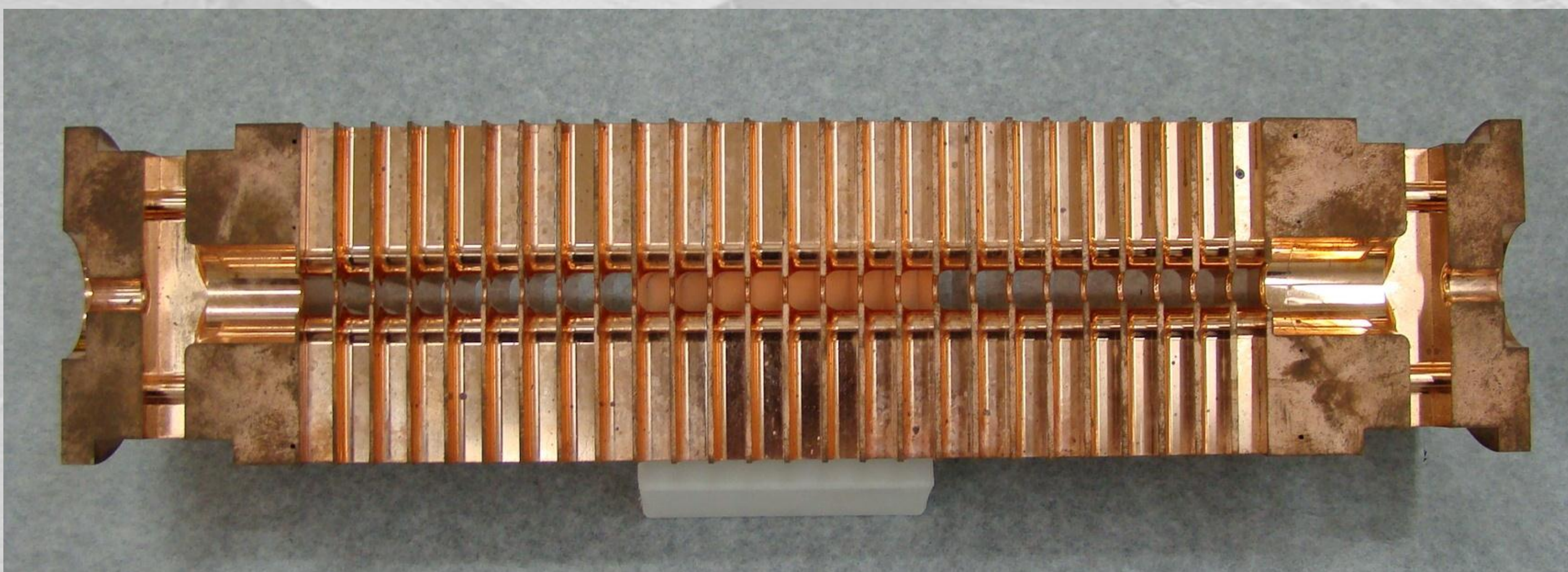




E_s/E_a H_s/E_a S_c/E_a^2

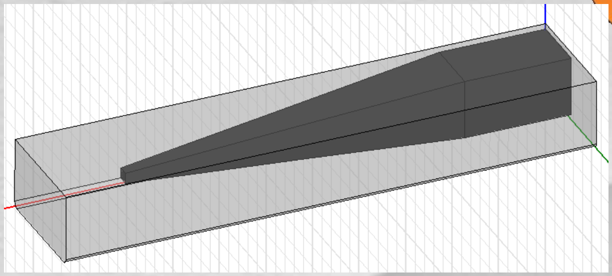


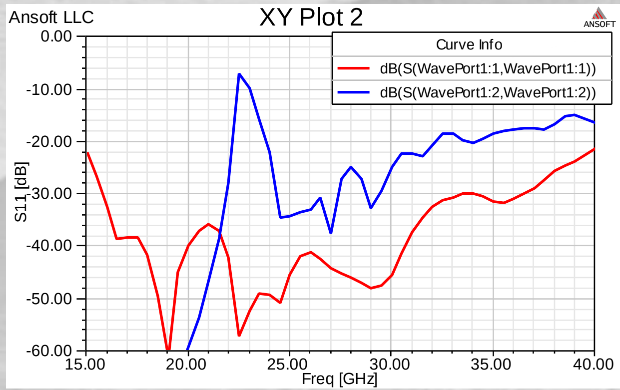
How it looks

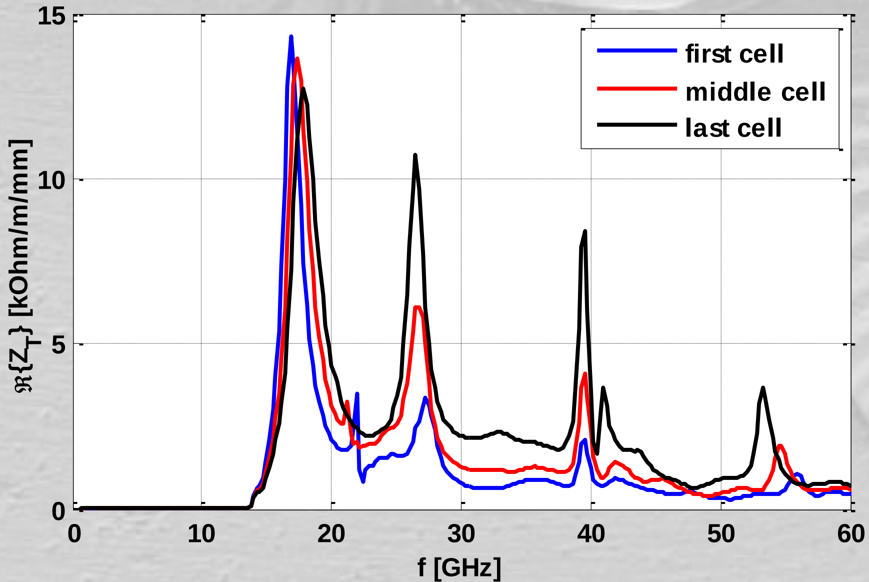


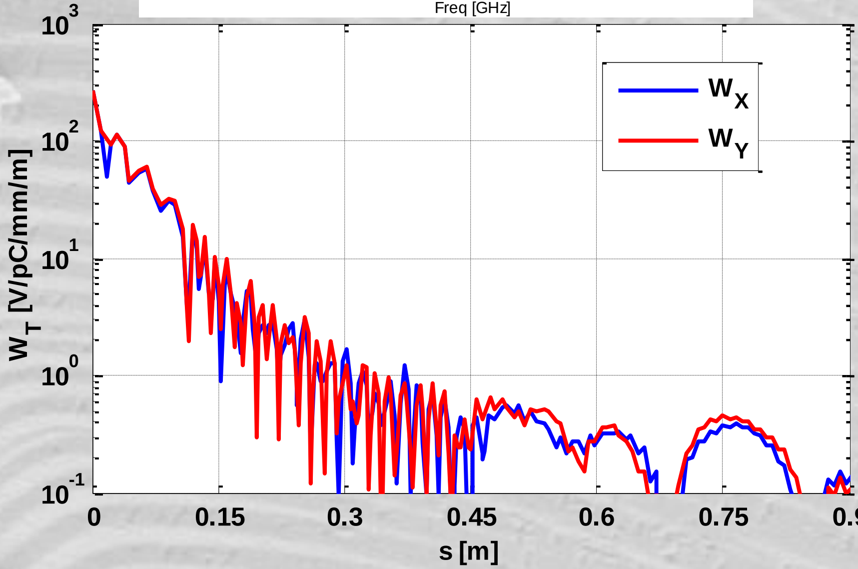
Higher-order mode damping

Cell	First	Middle	Last
Q-factor	11.1	8.7	7.1
Amplitude [V/pC/mm/m]	125	156	182
Frequency [GHz]	16.91	17.35	17.80







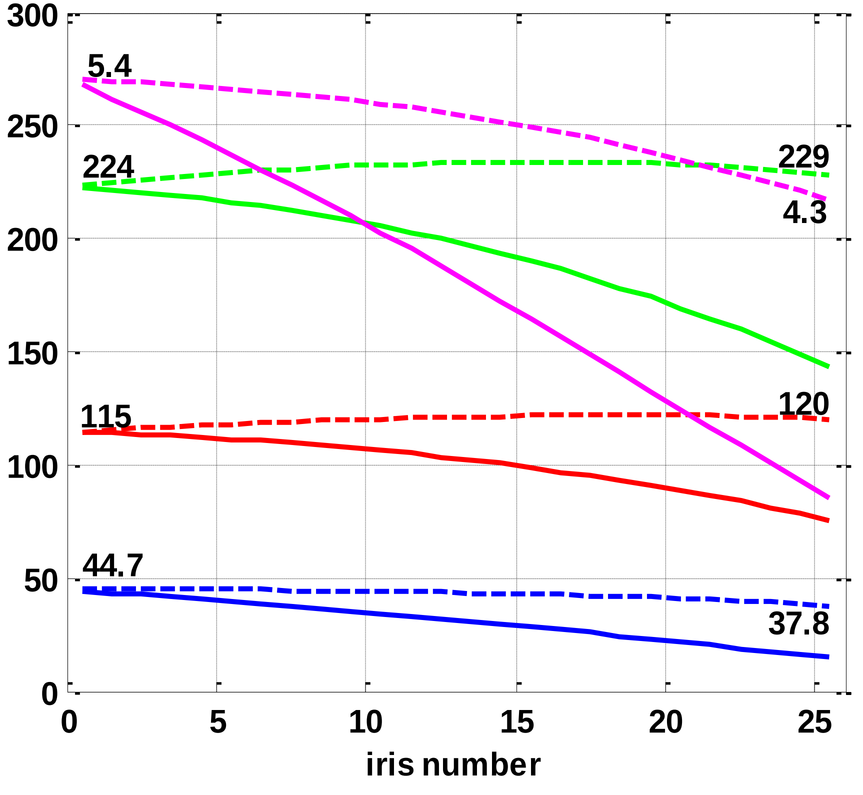


Accelerating structure characteristics cont.

The aperture radii range from 3.15 to 2.35 mm with iris thicknesses of 1.67 to 1.00 mm. The resulting rf parameters are:

	first	last
v_g [%c]	1.65	0.83
R'/Q [kΩ/m]	14.6	17.9
Q	5536	5738
R' [MΩ/m]	81	103

Whole structure properties



The fundamental mode properties are shown in the regular cells.

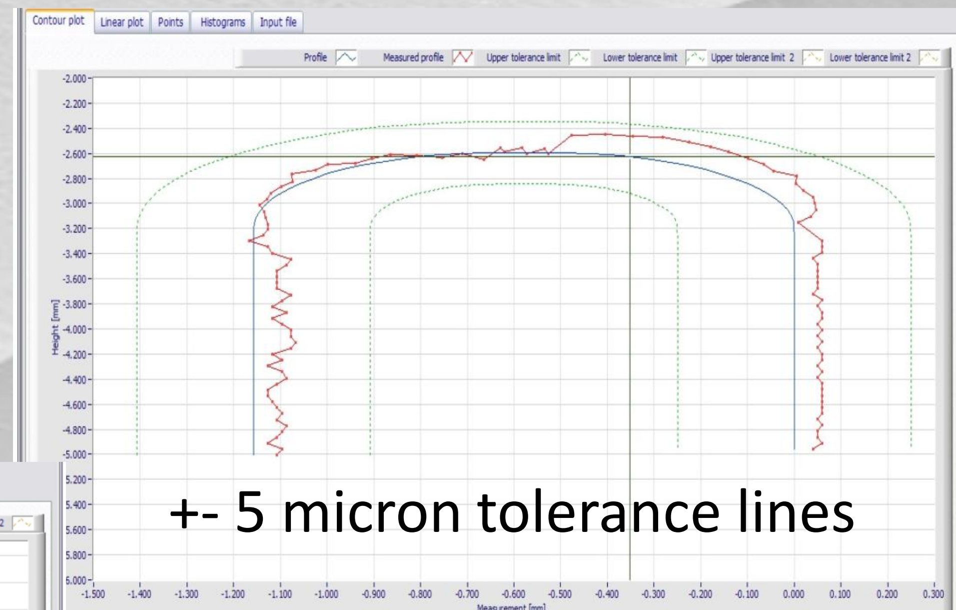
The traces from top to bottom are:

- Sc·50 [W/μm2](pink),
- surface electric field [MV/m](green),
- **accelerating gradient [MV/m](red),**
- pulse surface temperature rise [K](blue).

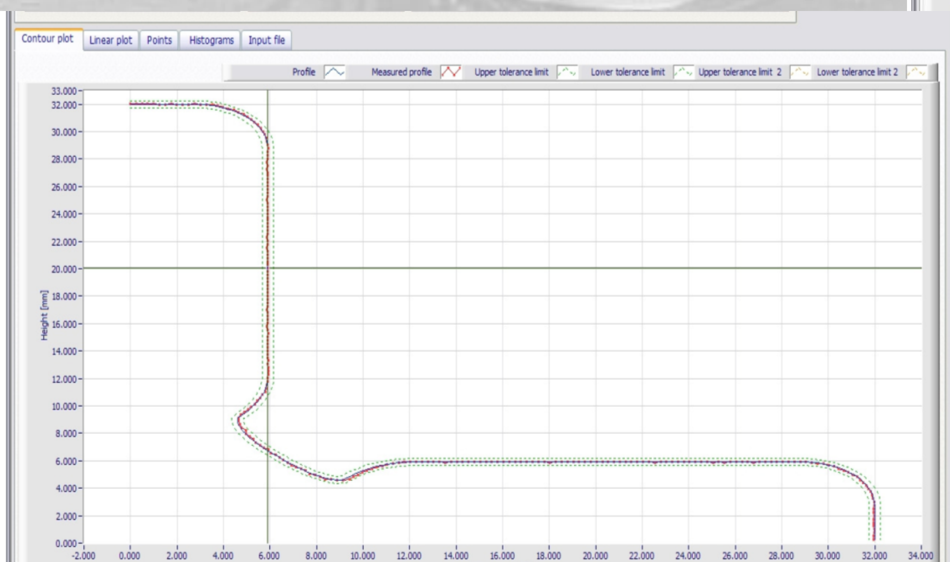
Dashed traces are unloaded and solid are beam loaded conditions.

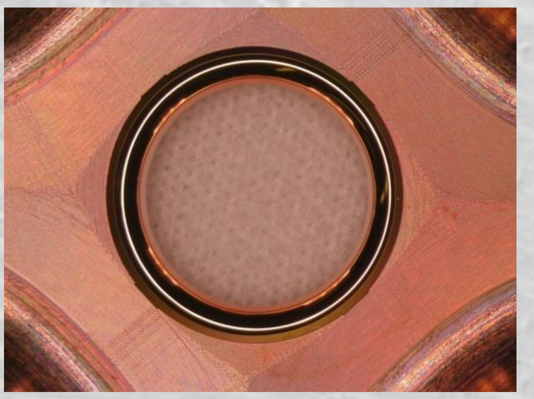
How to make 'em

Machining: OFHC copper diamond milled and turned disks with micron precision.



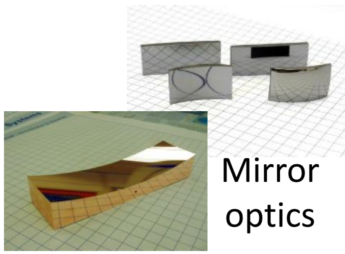
+- 5 micron tolerance lines





Evolution of the micron-precision market

The market for micron precision parts has evolved over the last decades.
Linear colliders are not alone.

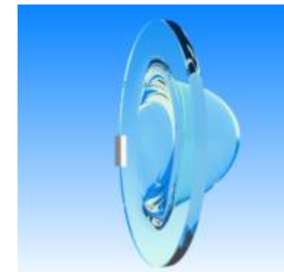


Mirror optics

Optical recording

Injection molding of contact lenses

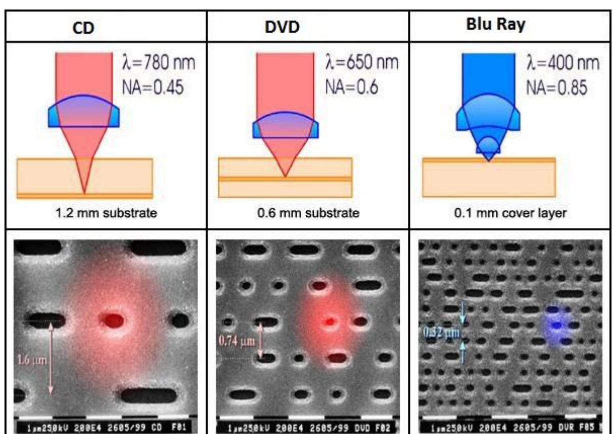
Imaging Optics



Freeform optics

1970's → 1980's → 1990's → 2000's → 2010's

Optical recording was the driving force to achieve higher accuracies



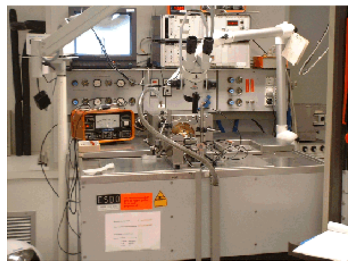
Form accuracy: 150 nm ⇨ 50 nm

Roughness Ra : 5 nm ⇨ 2 nm

Evolution of machining capability

Single point diamond turning

Up to the 1980's	1980's - 1990's	2000's - 2010's	Future ?
First machines at research institutes and universities	Start of industrialization • *Optical recording* • *contact lenses*	• *Larger machines* • *Multiple axis (X/Y/Z and C)*	• *Intelligent machines ?* • *Robotisation ?*



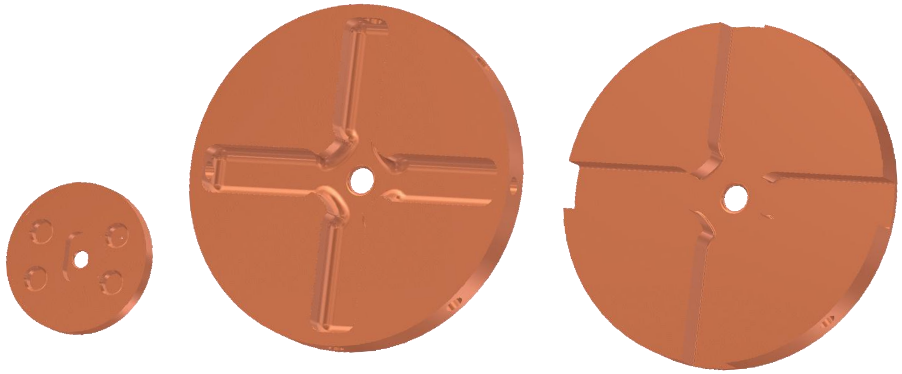
Ultra precision diamond milling *(lagging more than a decade behind on turning)*

Up to the 1990's	1990's - 2000's	2010's	Future ?
Limited to fly cutting • *mirror optics* • *Laser scanner mirrors*	Milling as add-on on lathes • *Lens arrays* • *Intra ocular lenses*	First proto type machines • *Micro fluidics* • *Accelerator parts*	• *Pallet machining?* • *Robotisation ?*

Current challenges for the basic technology

- BIGGER STRUCTURES, SAME TOLERANCES

  Started at ø35mm – now at ø80mm – in future up to ø200mm ?



- TIGHT ACCURACY SPECIFICATIONS FOR SERIES MANUFACTURING

***Moulds** for DVD optics :*
50 nm form accuracy on ø 2 mm
equals ratio of 1 / 40000

CLIC disk -> **series part**
2 µm accuracy on ø 80 mm
equals ratio of 1 / 40000

High accurate Machining

5-axis CNC turning milling machine

Technical characteristics:

X axis travel **350 mm**
Y axis travel **150 mm**
Z axis travel **300 mm**
B and C axis travel **360 degrees**

Swing capacity up to 20''
Air bearing Turning spindle 10,000 rpm
Air bearing Milling spindle 60,000 rpm

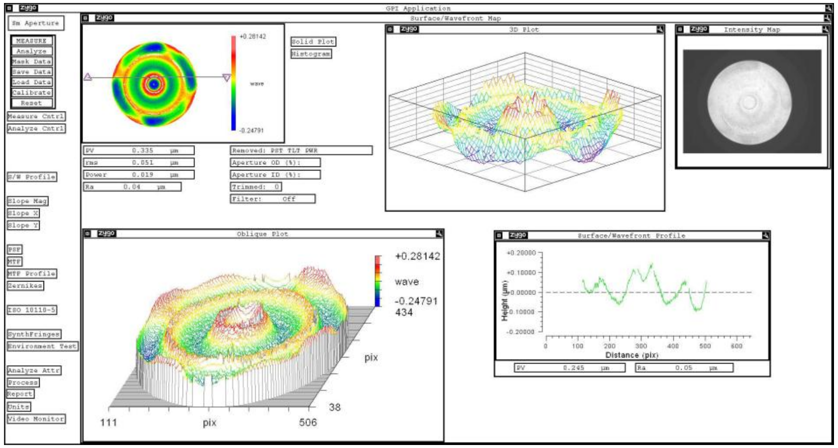
Precision
34 picometers resolution rules (0.034 nanometers)
Incremental programming **0.01 nanometer**
Axial and radial spindle error ≤ **25 nanometers**
B axis axial and radial error ≤ **100 nanometers**

Shape defect ≤ 0.15 µm on diameter 75 mm
Surface finish Ra ≤ 3.0 nanometers

Machine delivered on january 2011
First structure TD24WFM delivered on novembre 2011.

High Accuracy Machining

Aluminum mirror for satellite application on its support delivery



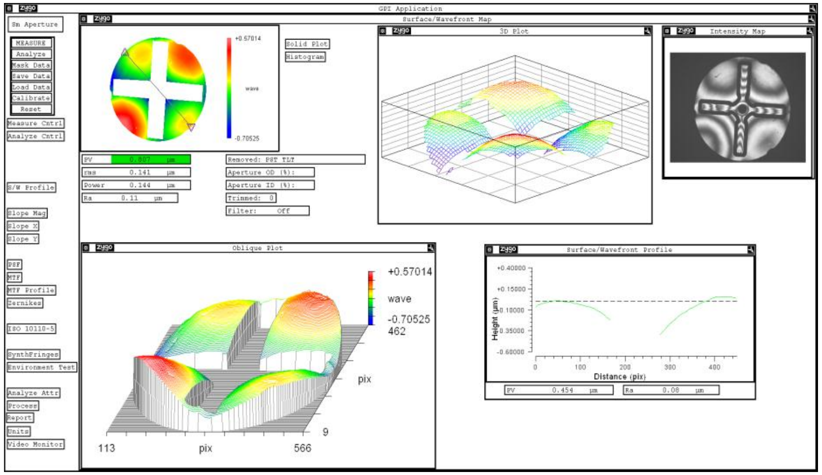
Results :

PV = 0.335 µm

Ra = 0.001 µm

RmS = 1,92 nm

Copper disk - accelerating structure



Results :

PV = 0.807 µm

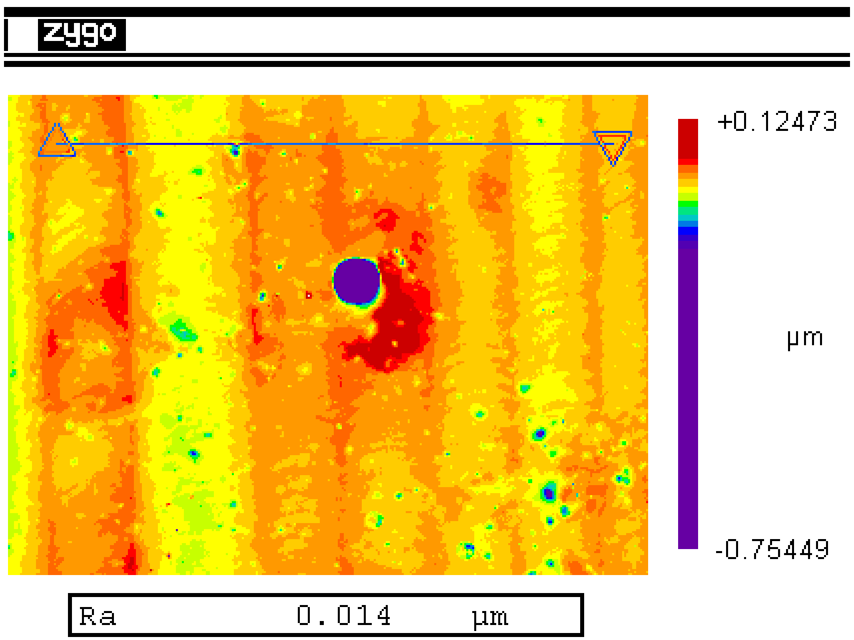
Ra = 0.002 µm

RmS = 1,72 nm

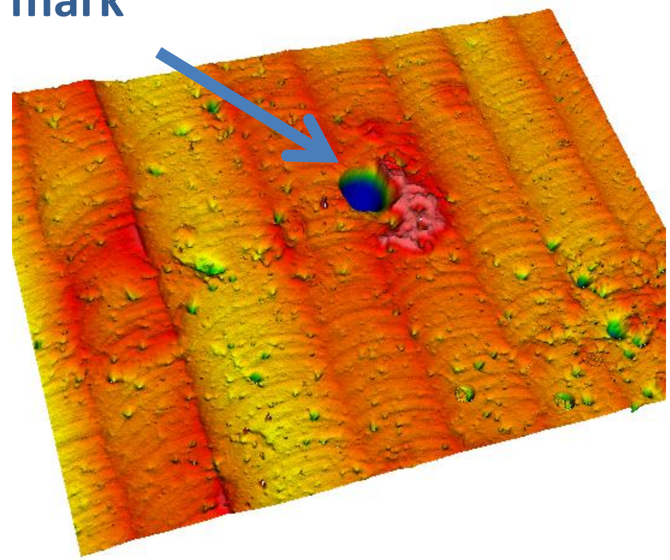
MECACHROME

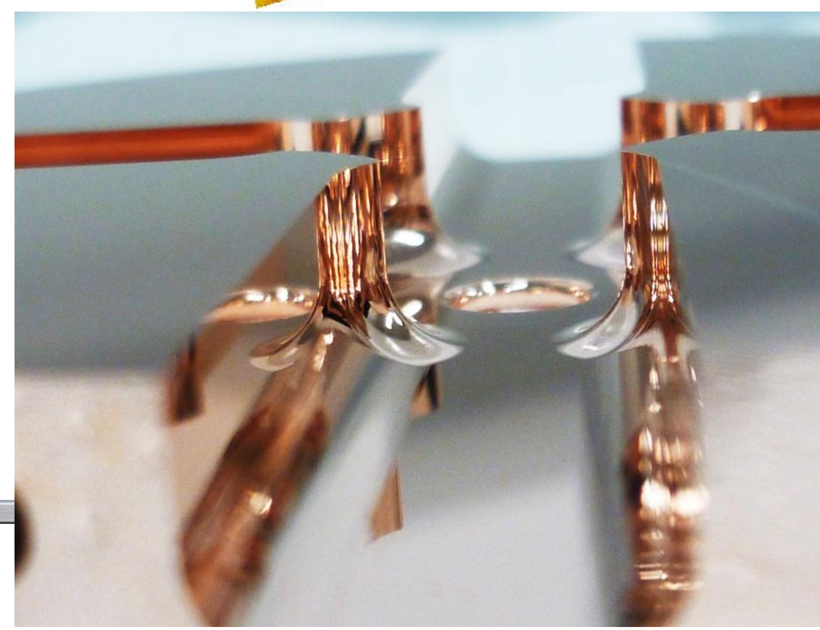
Milling surface finish improvement

Results

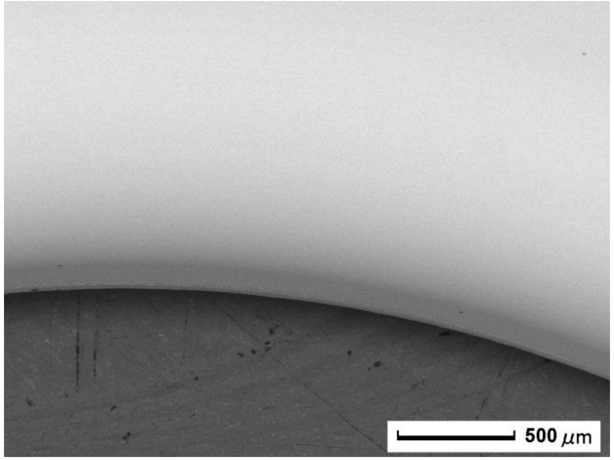


Métrology mark

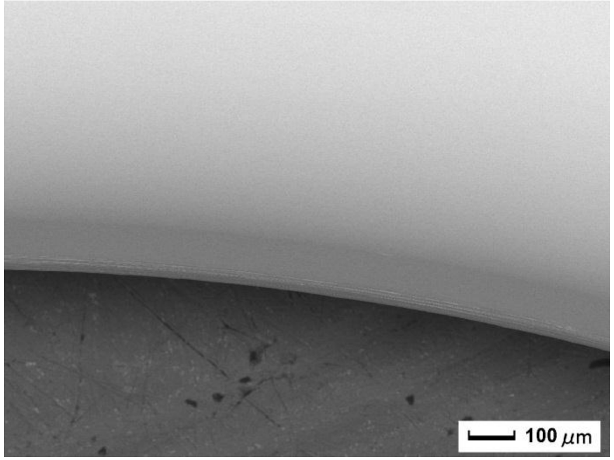




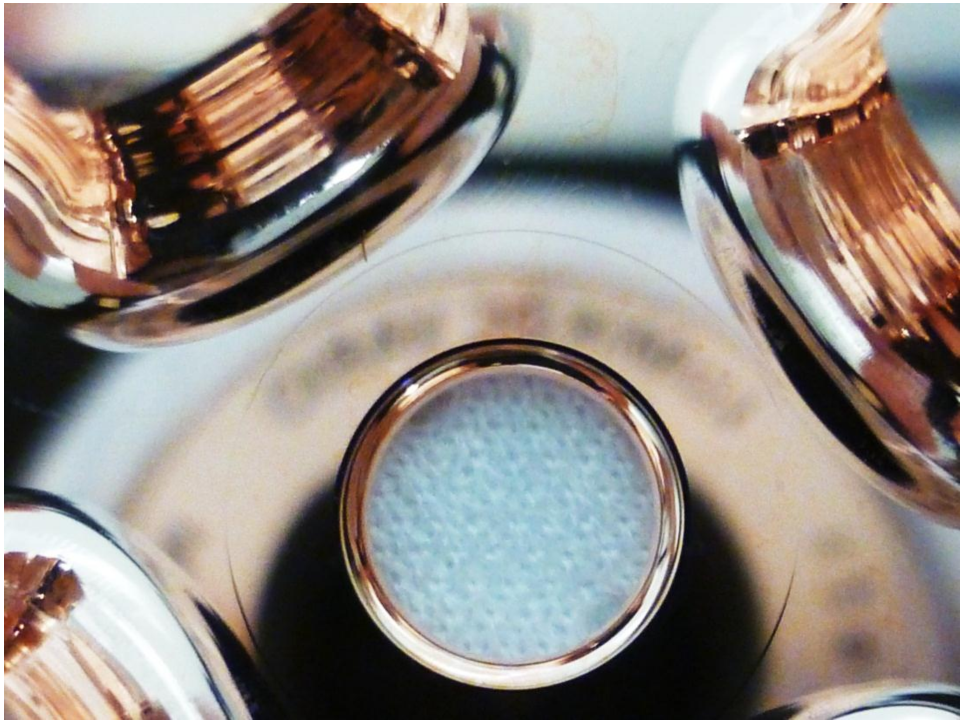
Iris machining



Ra between 2nm to 5nm

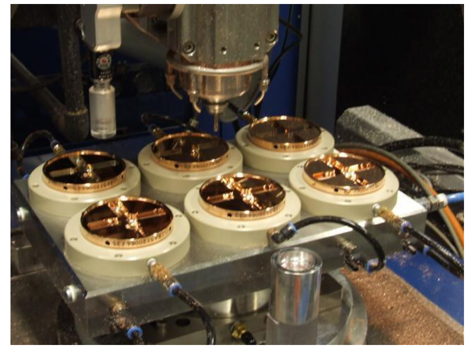


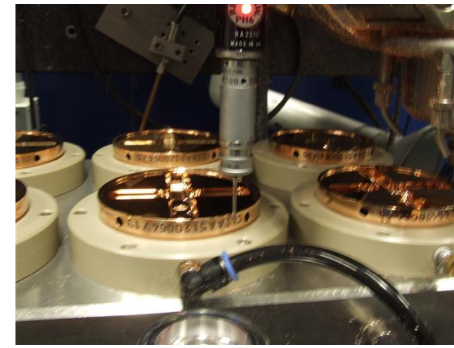
The machining of the iris start from diameter 20mm to erase milling perturbation in the center.
The height of the step is about 1µ.



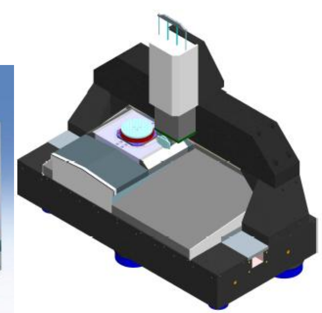
VDL ETG Industry Commitment

- Investments in new skills
  - H2 bonding
  - Micro milling
  - Pallet machining
  - On machine metrology





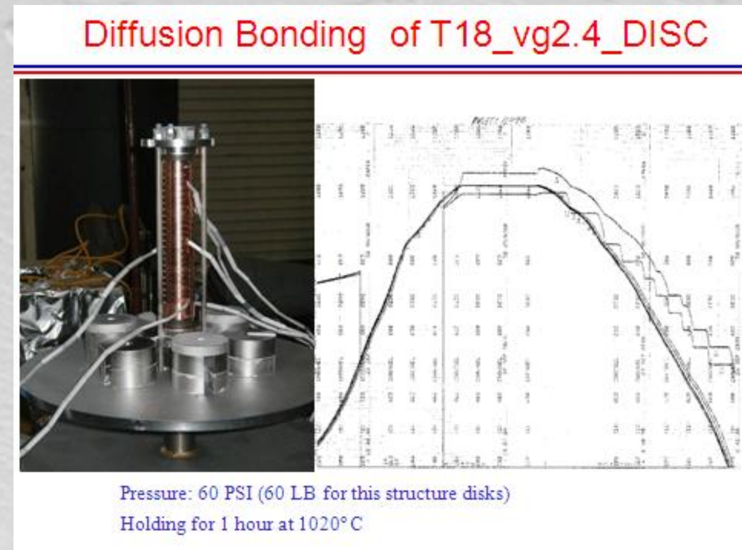
- Investments in people
  - Cooperation programs with schools, universities, institutes
  - Internal education
  - Career paths
- Investments in infrastructure
  - Equipment
  - New Facility



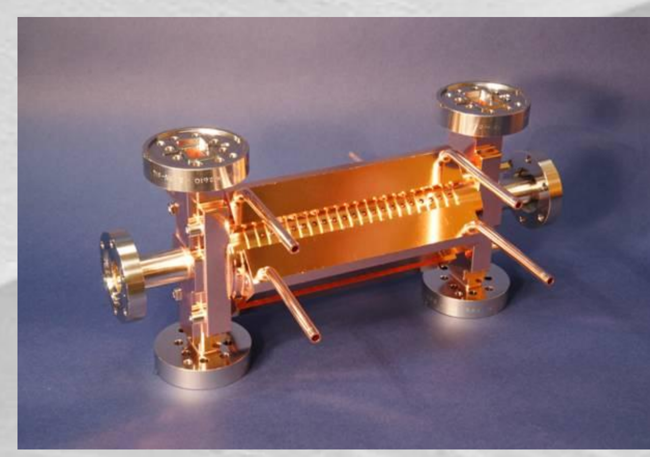
- **Guidance is required to steer investments in the right direction**

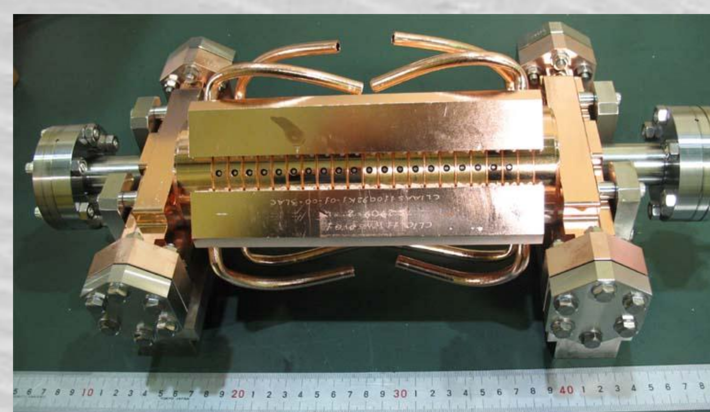
Accelerating structures – manufacture

Stacking disks



Temperature treatment for high-gradient





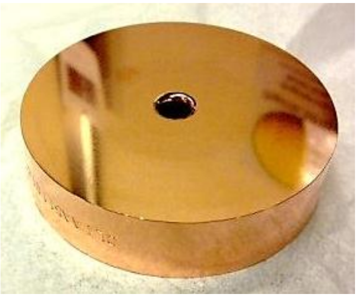
Structures ready for test

Diffusion bonding of couplers under H_2 at 1 bar

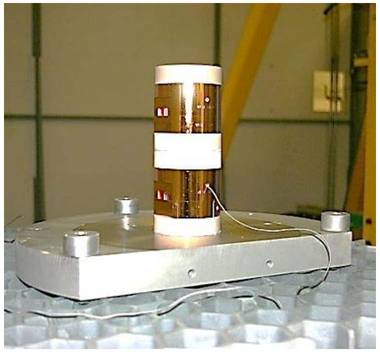
- Done at Thales Electron Devices (TED) – Velizy (France)
- Degreasing and etching at CERN before bonding
- Applied weight: 43 kg equivalent to ~ 0.13 MPa; thermal cycle: flat top at 1035° C during 1h30
- Process validated on a test coupler: observation of crossing grains in the joint plan
- Some deformations observed on the outer faces after bonding : ~0.1 mm -> re-machining done

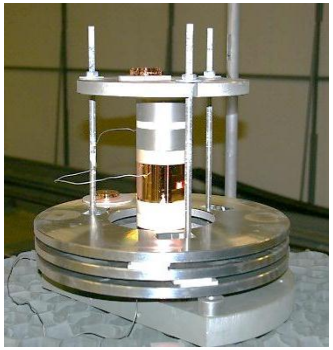
Coupler

Extremity cell

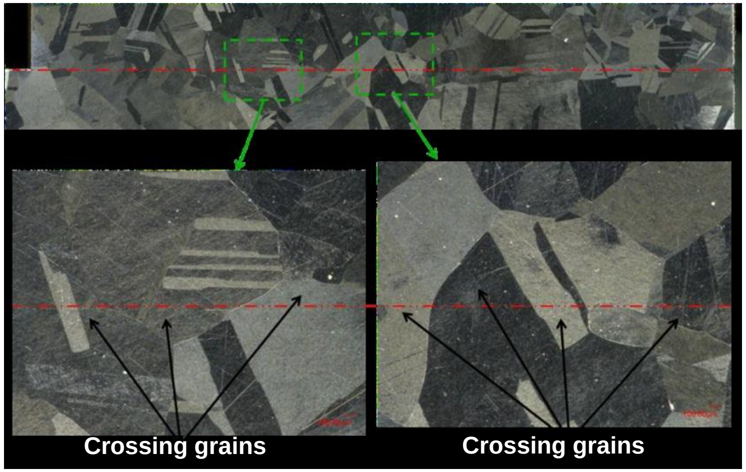


Assembly of couplers in the furnace

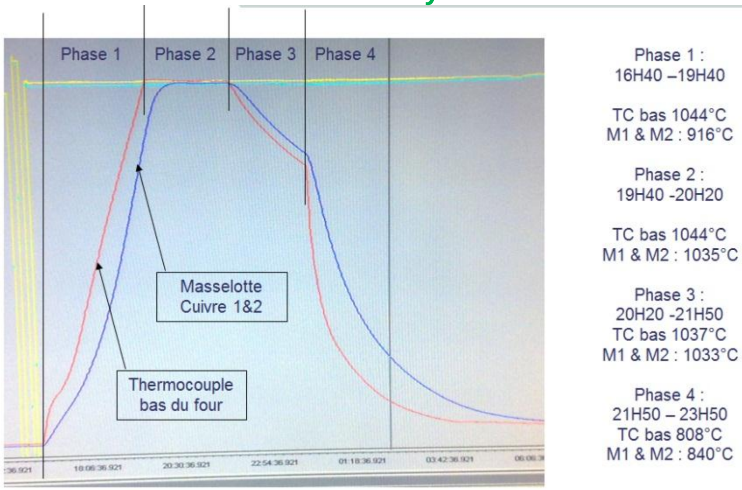




SEM observation of bonding plan after cutting



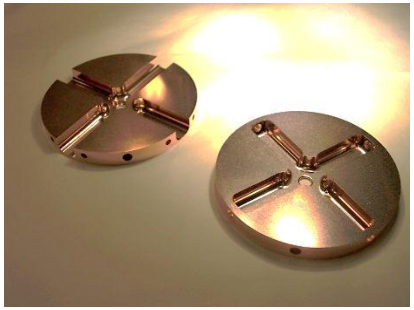
Thermal cycle



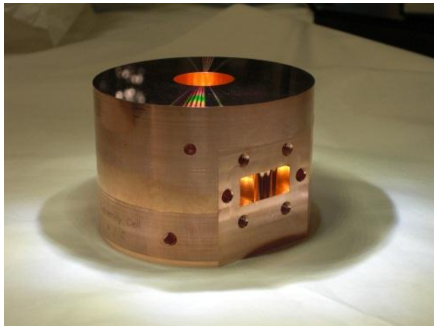
Diffusion bonding of structure under H_2 at 1 bar

- Also done at TED with degreasing and etching at CERN before bonding
- Applied weight: 33.7 kg equivalent to ~ 0.08 – 0.12 MPa;
- Same thermal cycle as couplers but with flat top at 1010° C
- No deformations observed on the external diameter after bonding

Disks after etching



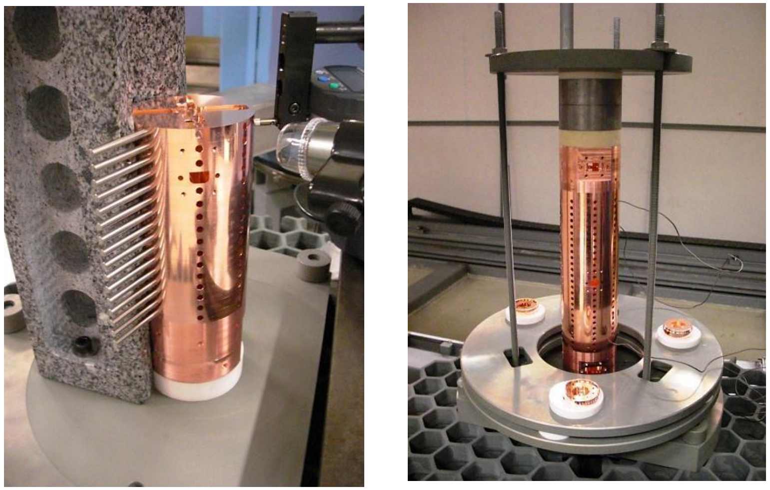
Coupler



Structure n°1

Structure n°2

Assembly of disks in the furnace



Geometrical measurements on external diameter after bonding

Alignment = 9µm for ACS#1 and 12.6 µm for ACS#2

Angle = 90.0514° for ACS#1 and 90.0087° for ACS#2

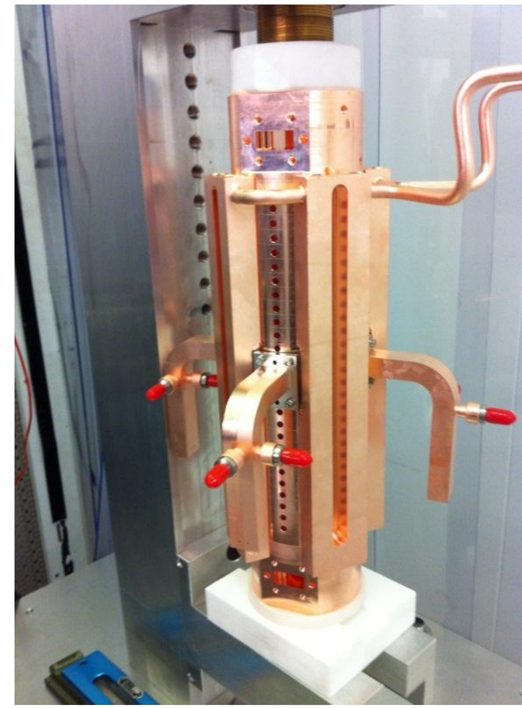
Assembly of accelerating structure accessories

- Done at Bodycote – Villaz (France) and CERN
- Tuning studs and cooling circuits brazed with copper gold alloy below 1000° C under vacuum
- Good tightness and no drip of alloys observed in the cells
- Assembly test by screwing of WFM waveguides OK

Assembly of tuning studs

Assembly of cooling circuits

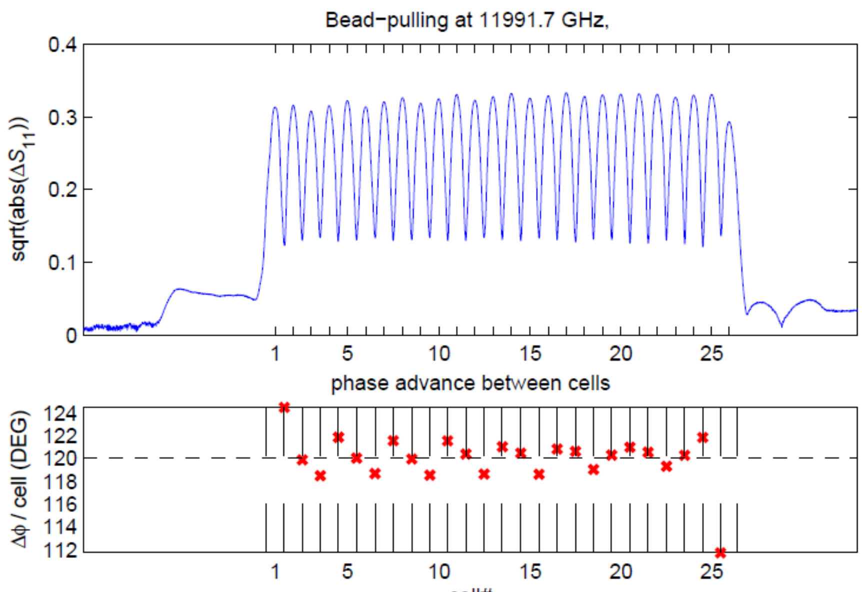
Assembly of WFM waveguides



S. Lebet

Bead-pull and RF tuning of structure n°1

- Done at CERN by Jiaru Shi the 22th of Feb. 2012
- Target frequency: 11991.65 MHz (considering freq. shift due to wire, nitrogen and temperature of 21.6 deg)
- All disks tuned with only one stud used for each disk
- <u>Very successful tuning</u>



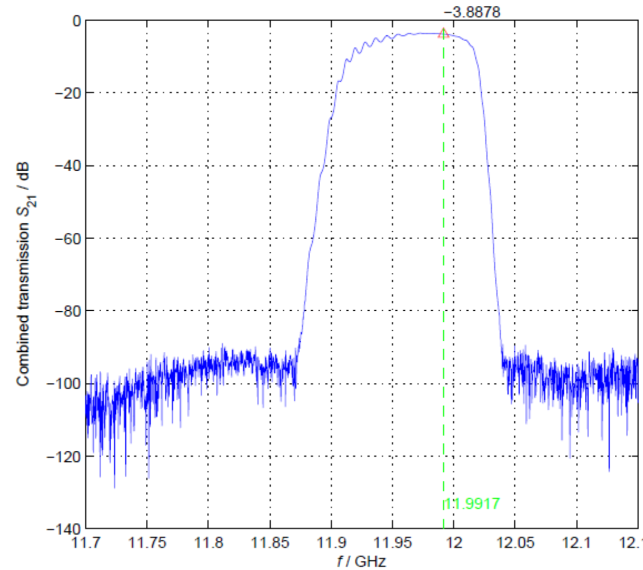
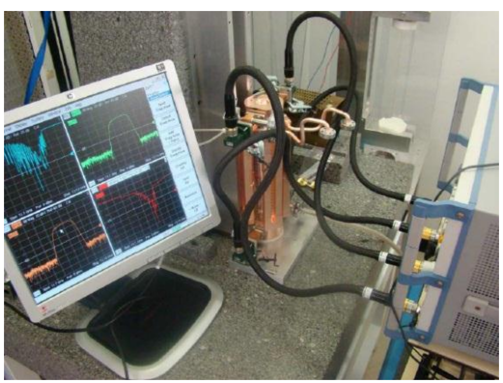


Figure 8: Combined transmission from input to output



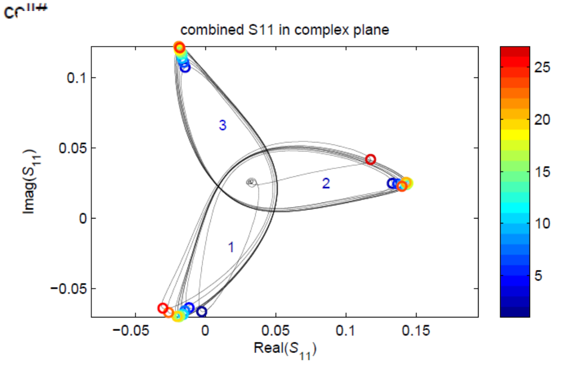


Figure 12: Bead-pulling at 11991.7 GHz

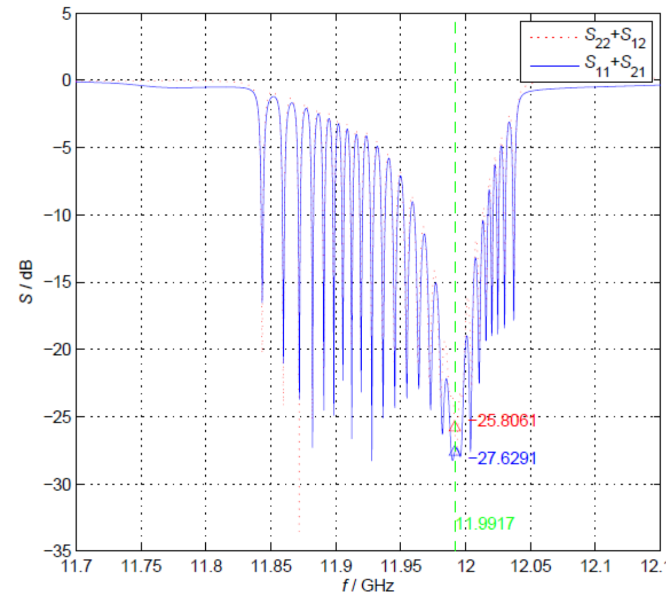
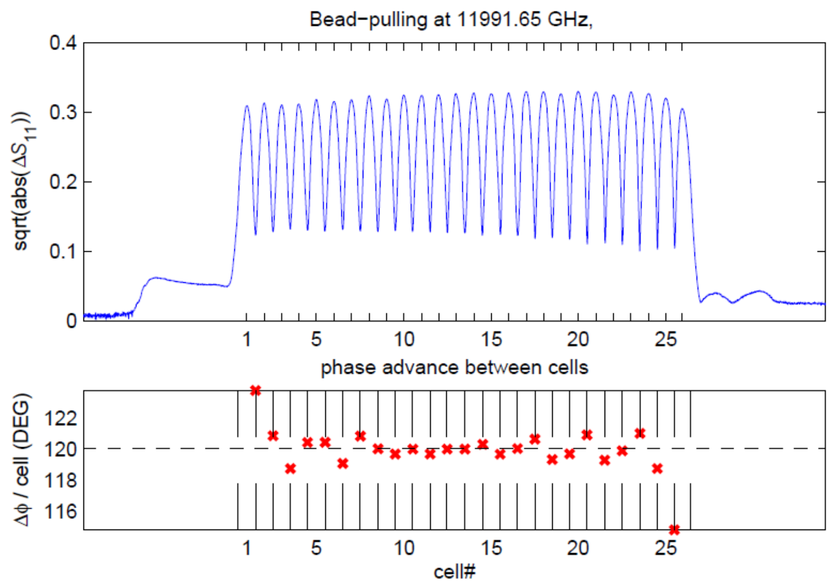
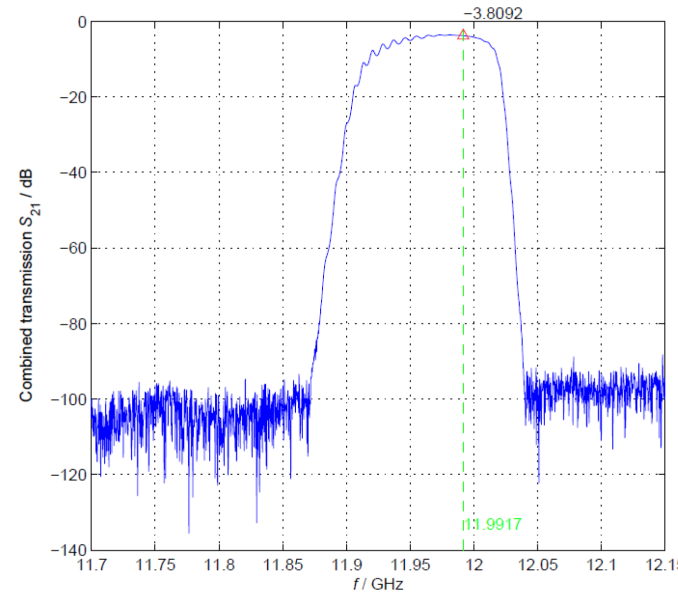


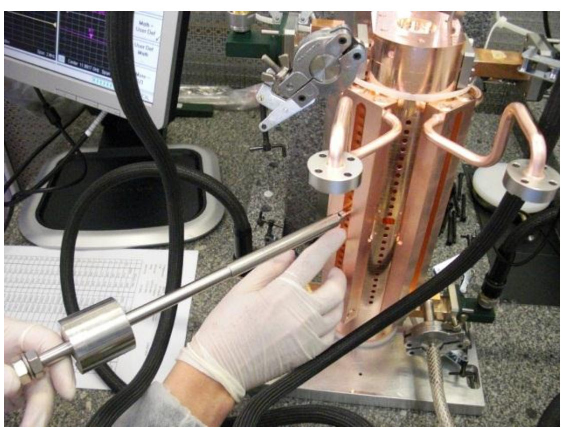
Figure 4: Reflection at input

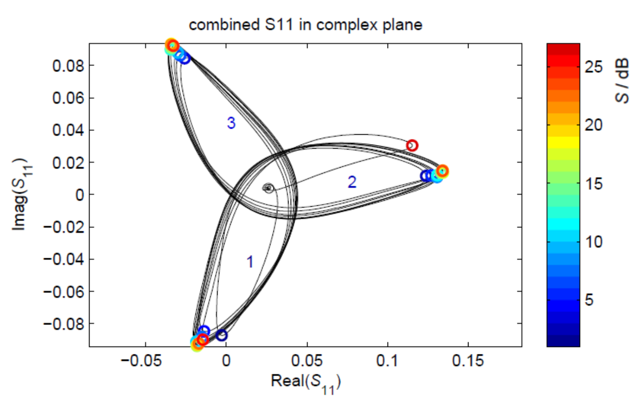
Bead-pull and RF tuning of structure n°2

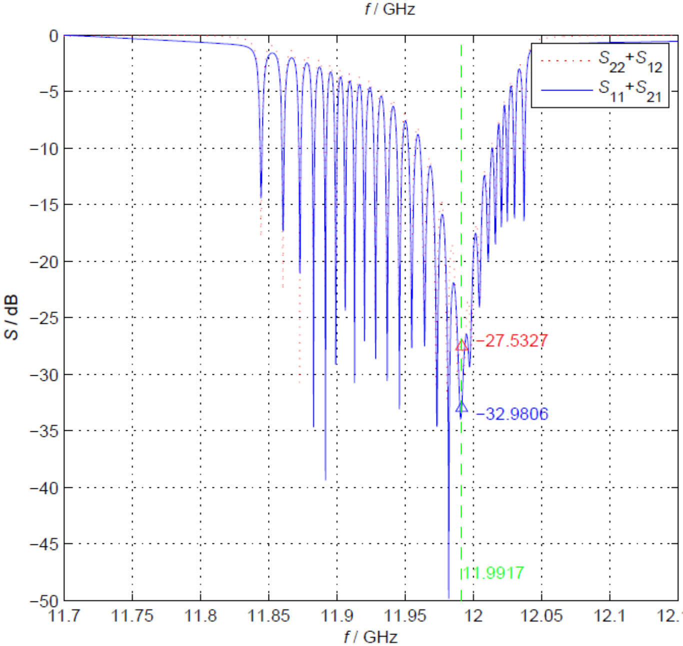
- Same procedure as structure N1, done the 6th of March 2012
- Disk 13 tuned by -10 MHz (the 4 studs were used), all the other disks were tuned +/- 3MHz like structure N1
- Very successful tuning also



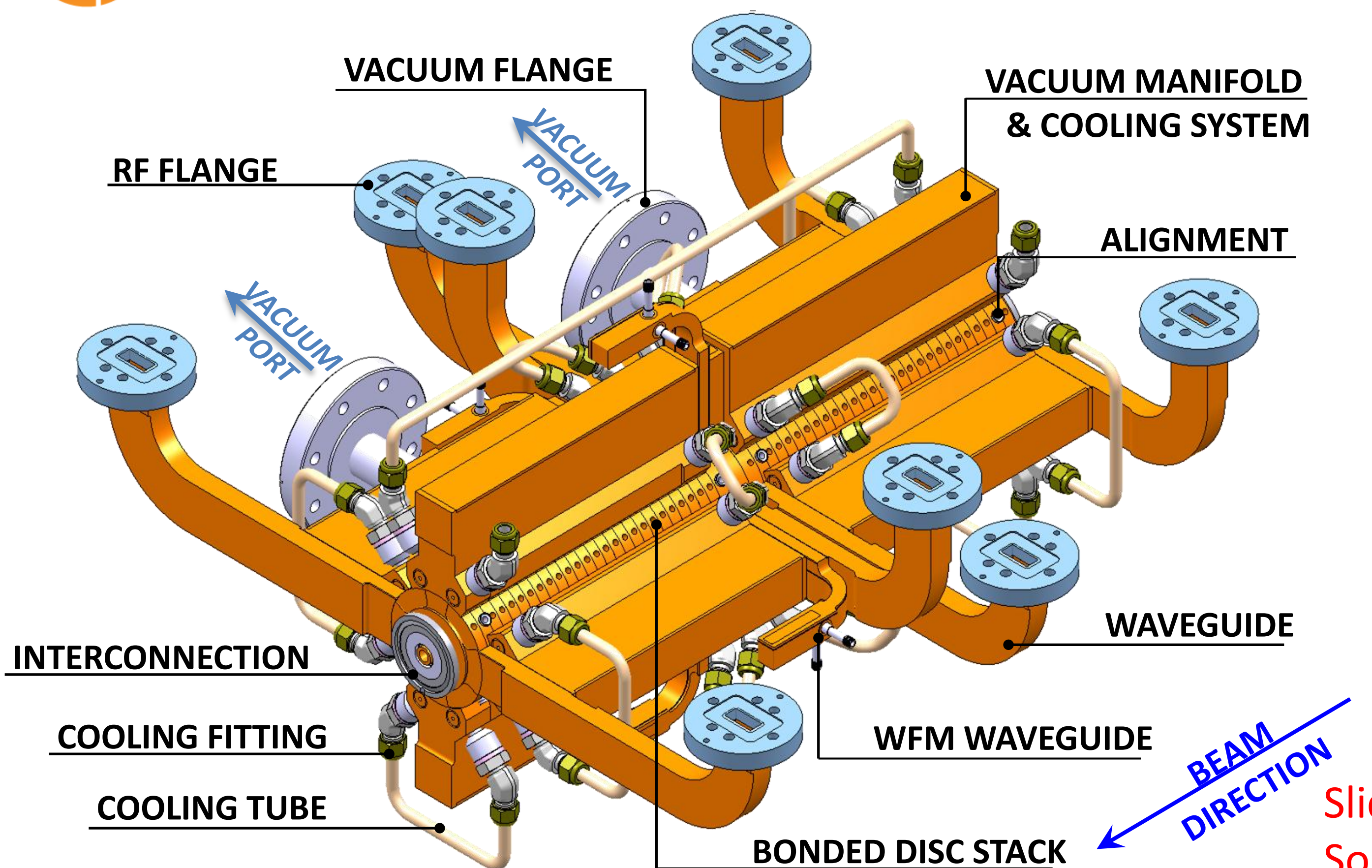


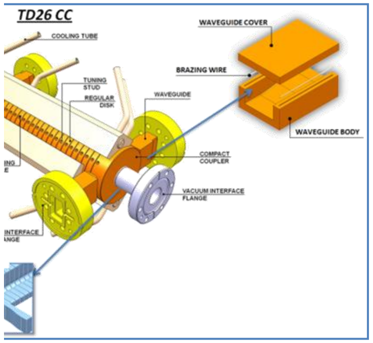






Engineering Design Overview

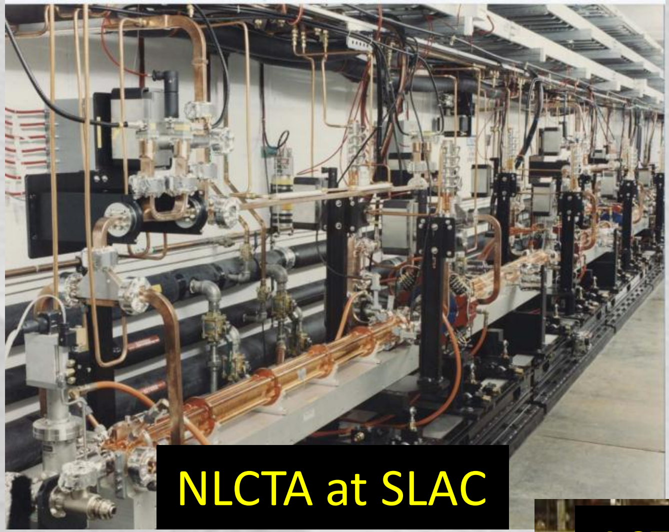


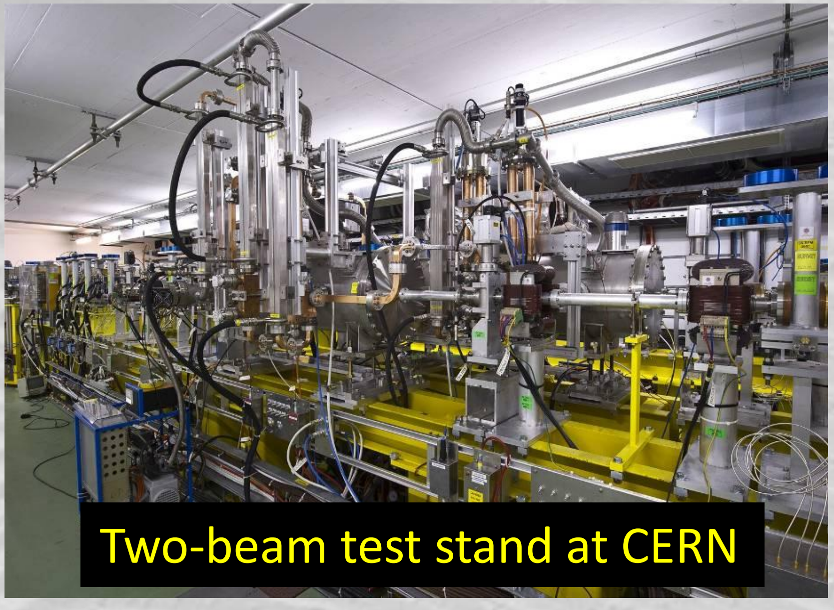


Slide from Anastasiya Solodko

- Compact coupler design (already in TD26 CC);
- The body of an AS formed by high-precision copper discs joint by diffusion bonding at 1040 °C;
- Two AS are brazed together to form a superstructure (SAS);
- The SAS has 8 vacuum manifolds and 4 Wakefield Monitor (WFM) waveguides;
- The cooling system is integrated into the vacuum manifolds in order to provide a more compact technical solution.

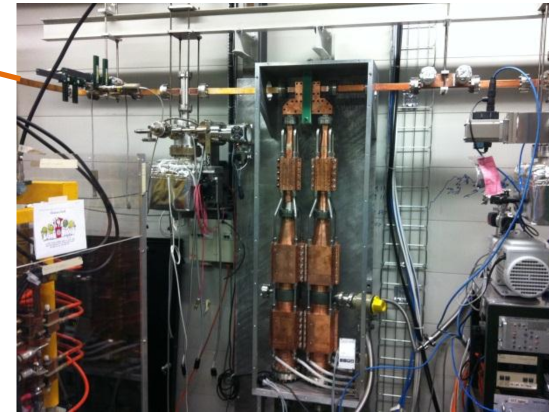
Prototype accelerating structure test areas





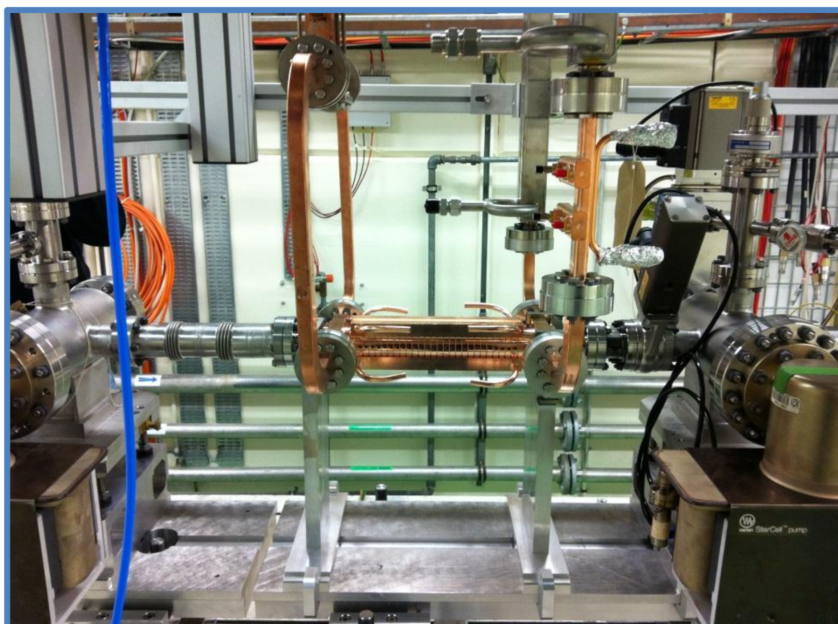
Status of the 12GHz standalone test stand

- WG network and LLRF finished
- Final vacuum infrastructure installation end of June
- Modulator flat top tuning by Scandinova done
- Klystron conditioned up to 40MW, 500ns, 50Hz with loads (50MW, 300ns, 50Hz)
- Pulse compressor operation started after FAT of modulator

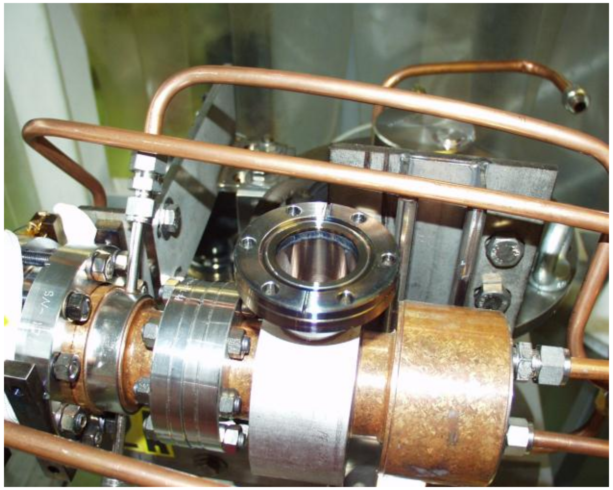


Gallery

Bunker



Klystron



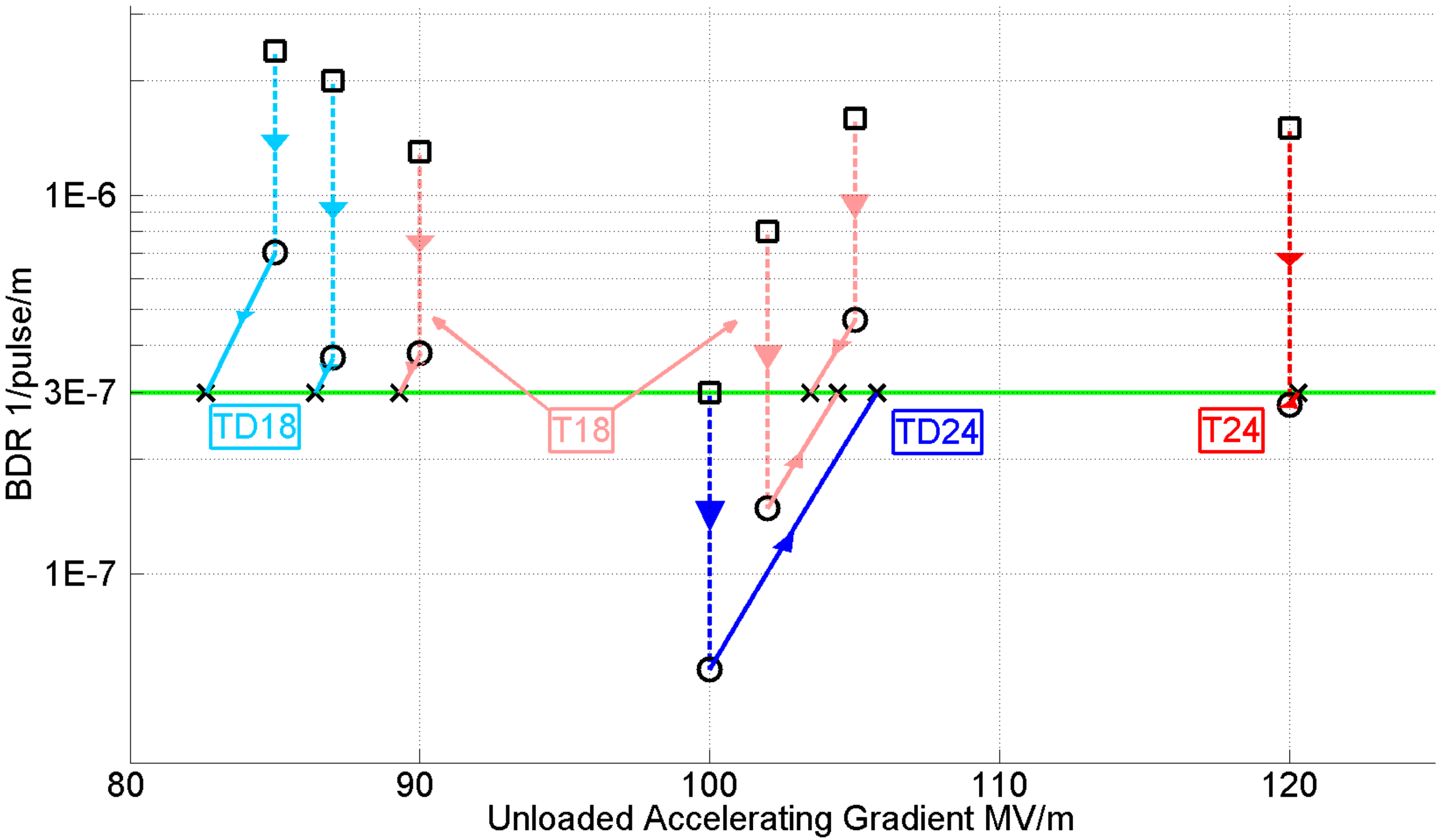
XL5 klystron, a scaled version of the successful XL4 klystron developed at SLAC

- Delivers 50MW, 1.5us long rf pulses with 50Hz repetition rate at 400kV, 300A, 600W rf drive power
- Working frequency 11.99424GHz
- Five klystrons built by SLAC
- Conditioned and tested at SLAC

- Extraordinary robust, survived a vacuum leak, a gun realignment and an overheating solenoid without any performance decrease so far…

More details in: SLAC-PUB-14377

Accelerating gradient test status: 4-9-2012

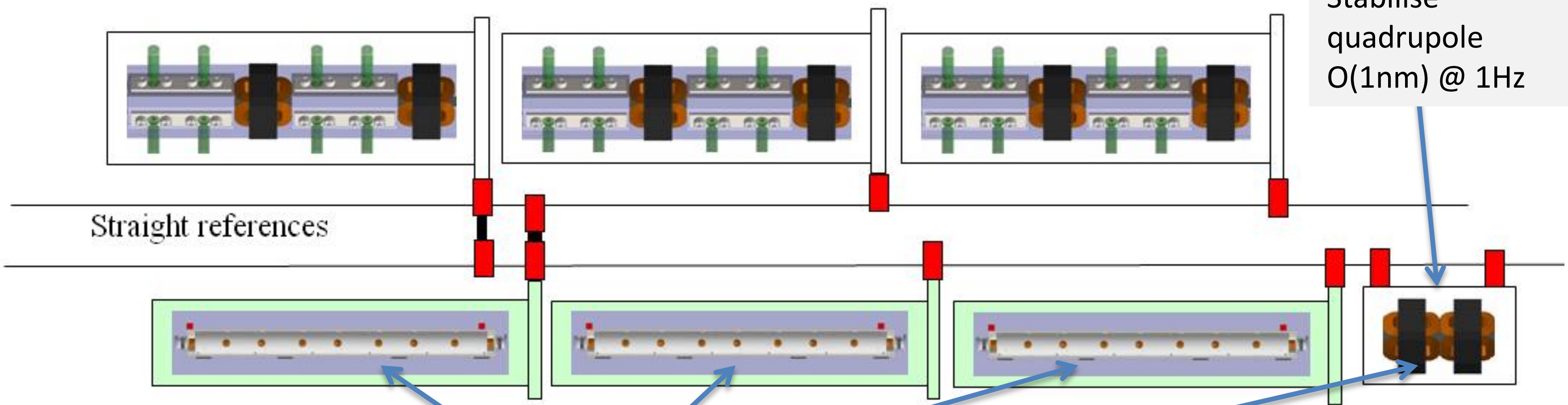


Accelerating structure parameters

Average loaded accelerating gradient	100 MV/m
Frequency	12 GHz
RF phase advance per cell	2π/3 rad.
Average iris radius to wavelength ratio	0.11
Input, Output iris radii	3.15, 2.35 mm
Input, Output iris thickness	1.67, 1.00 mm
Input, Output group velocity	1.65, 0.83 % of *c*
First and last cell *Q*-factor (Cu)	5536, 5738
First and last cell shunt impedance	81, 103 MΩ/m
Number of regular cells	26
Structure length including couplers	230 mm (active)
Bunch spacing	0.5 ns
Bunch population	3.72×10^9
Number of bunches in the train	312
Filling time, rise time	67 ns, 21 ns
Total pulse length	243.7 ns
Peak input power	61.3 MW
RF-to-beam efficiency	28.5 %
Maximum surface electric field	230 MV/m
Maximum pulsed surface heating temperature rise	45 K

Main Linac Tolerances

Stabilise quadrupole O(1nm) @ 1Hz

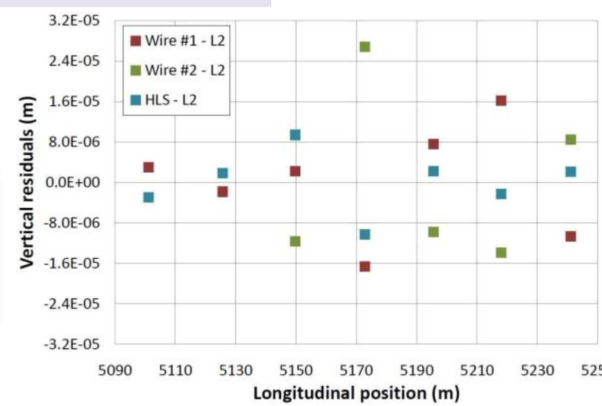


1) Pre-align BPMs+quads accuracy O(10µm) over about 200m

2) Beam-based alignment

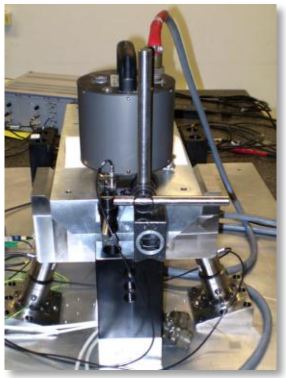
3) Use wake-field monitors accuracy O(3.5µm)

- Test of prototype shows
  - vertical RMS error of 11µm
  - i.e. accuracy is approx. 13.5µm

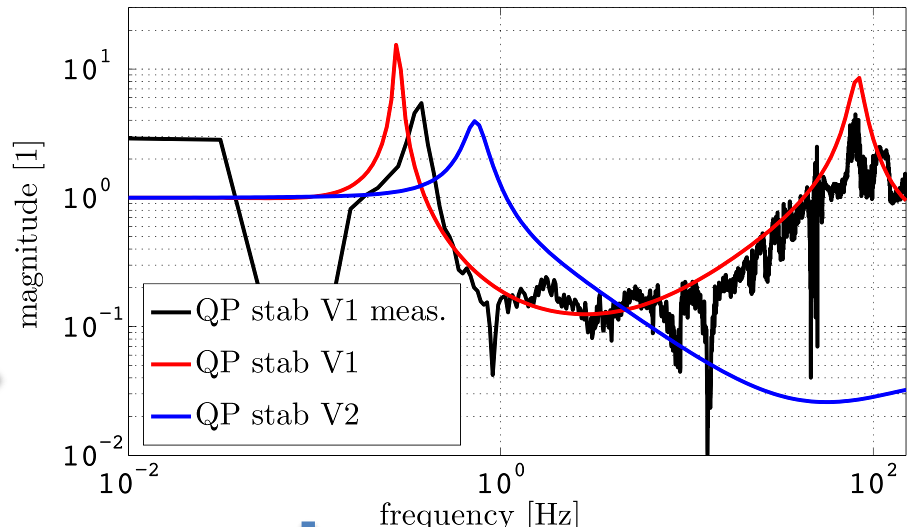


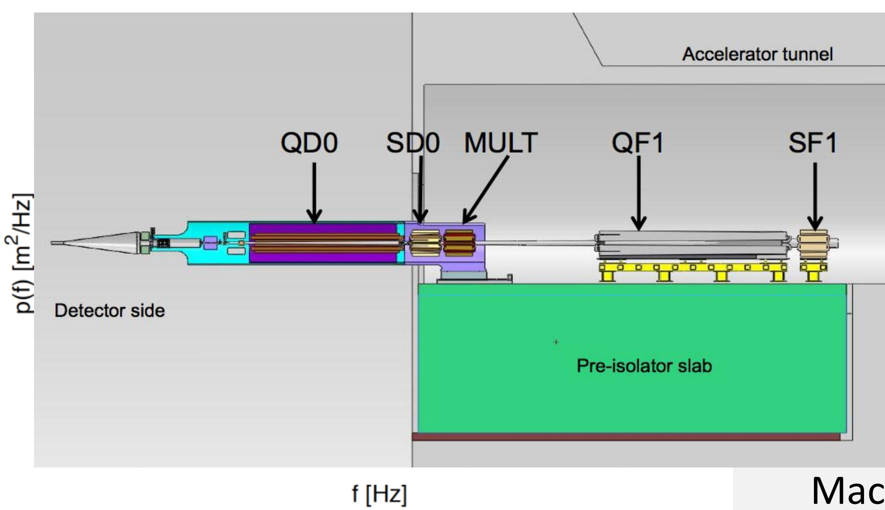
Active Stabilization

Typical quadrupole jitter tolerance O(1nm) in main linac and O(0.1nm) in final doublet



Final Focus QD0 Prototype





Code

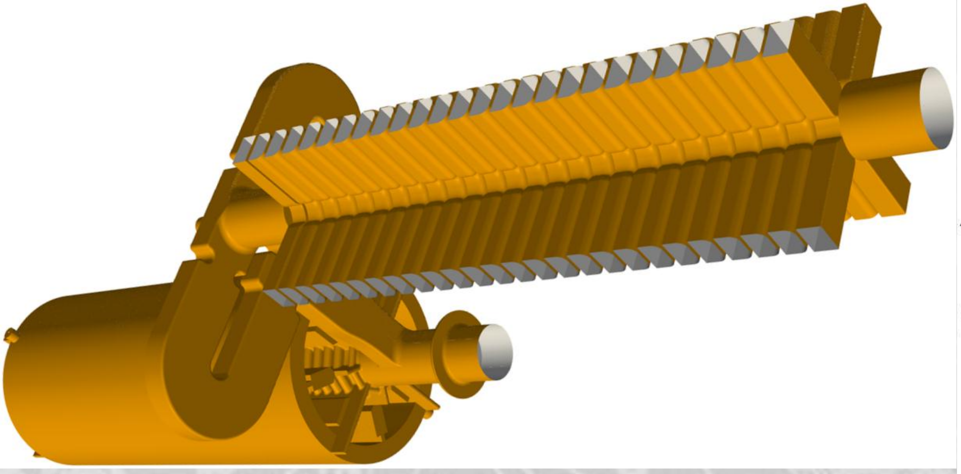
Machine model
Beam-based feedback

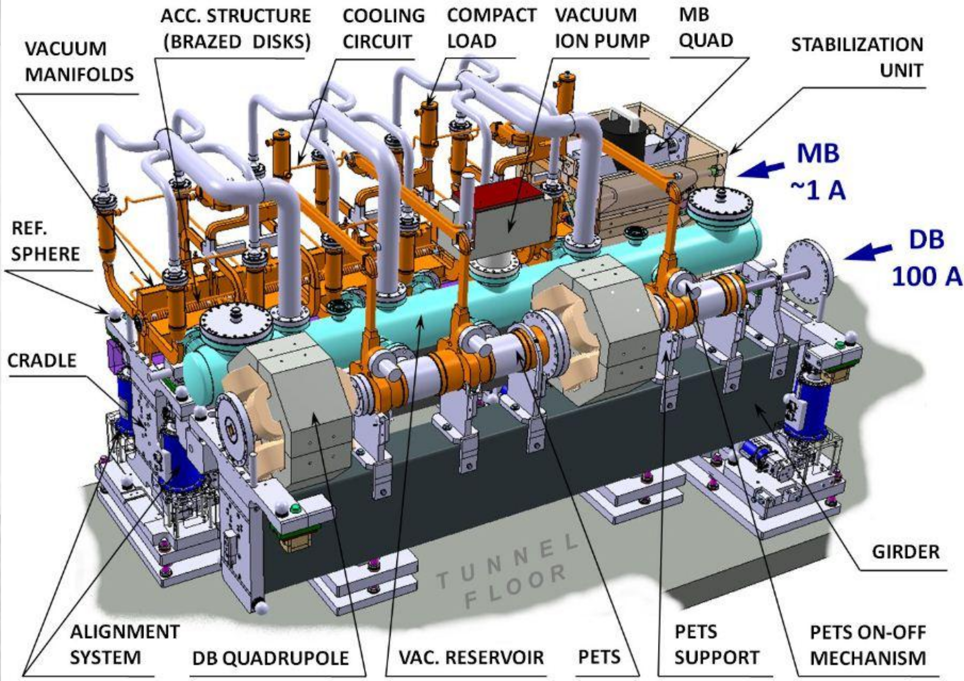
Luminosity achieved/lost [%]

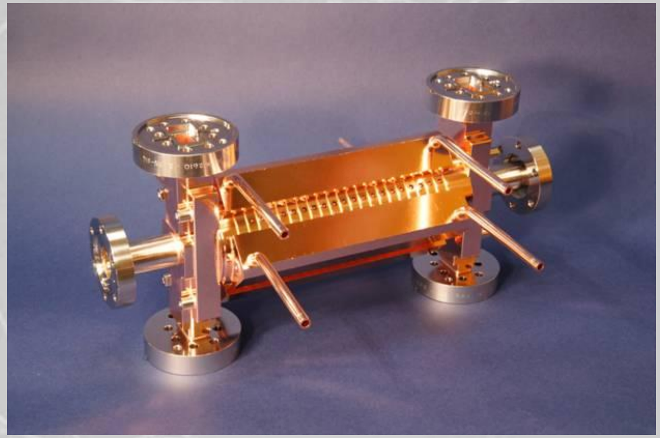
	B10
No stab.	53%/68%
Current stab.	108%/13%
Future stab.	118%/3%

Close to/better than target

Elements of CLIC two-beam







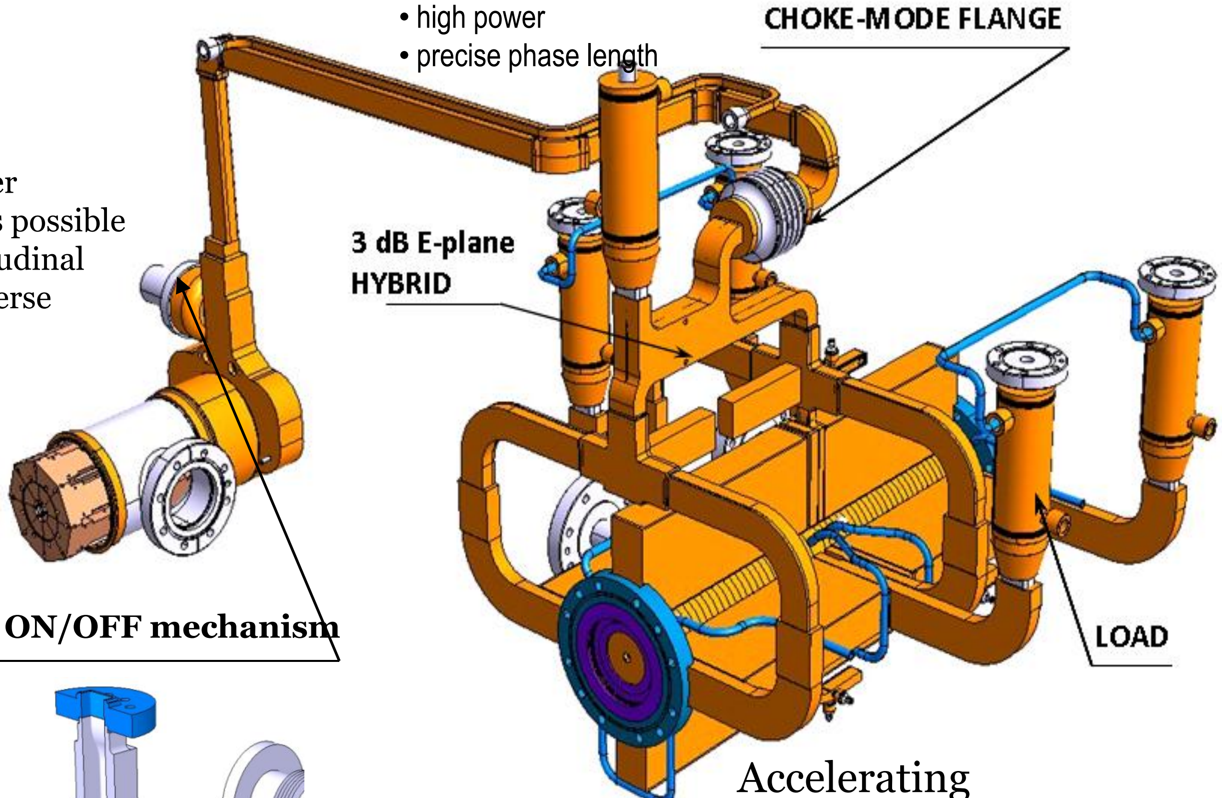
Two-beam RF components

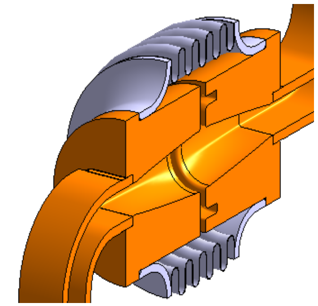
Waveguide network

- high power
- precise phase length

PETS

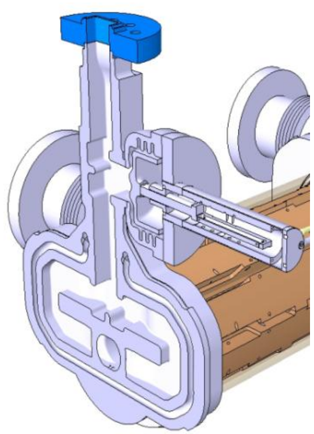
•high-power
•as short as possible
•low longitudinal and transverse impedance





Choke mode flange

- independent alignment of main and drive beam

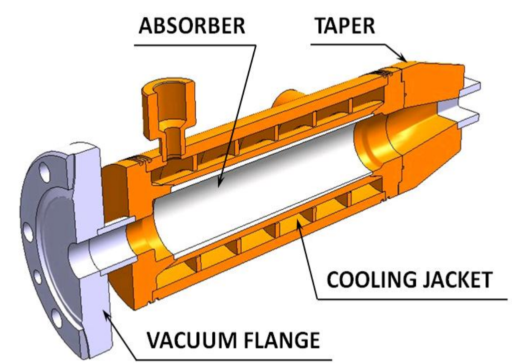


On/ramp/off

•necessary (?) to react to breakdown and/or failure

Accelerating structure

•high-gradient
•as long as possible
•micron precision
•transverse wake-field suppression



The early days of multi-TeV linear colliders

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-LEP-RF/86-06

and

CLIC NOTE 13
13.2.86

A TWO-STAGE RF LINEAR COLLIDER
USING A SUPERCONDUCTING DRIVE LINAC

W. Schnell

Abstract

The efficiency from RF input to beam power of a normal conducting travelling-wave linac can be raised above 5% albeit at the price of a very short power pulse and an appreciable but probably correctible energy spread. Compensated multibunch operation may yield 30% efficiency but higher order wakefield problems have to be solved and a suitable final focus system must be found. The worst remaining problem seems to be the economic and efficient generation of peak RF power. The solution proposed here consists of a limited number of CW UHF klystrons, a superconducting UHF drive linac and a lightly bunched drive beam of several GeV average energy, transferring energy from the superconducting linac to the main linac via short sections of transfer structures. The power balance of this scheme is analysed and it is found that overall efficiency can be very high. Very dense drive bunches are required. Present-day performance of superconducting cavities is already sufficient to make the scheme viable at main linac accelerating gradients approaching 100 MV/m.

Geneve, Switzerland
February 1986

CLIC Note 38
(May, 1987)

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

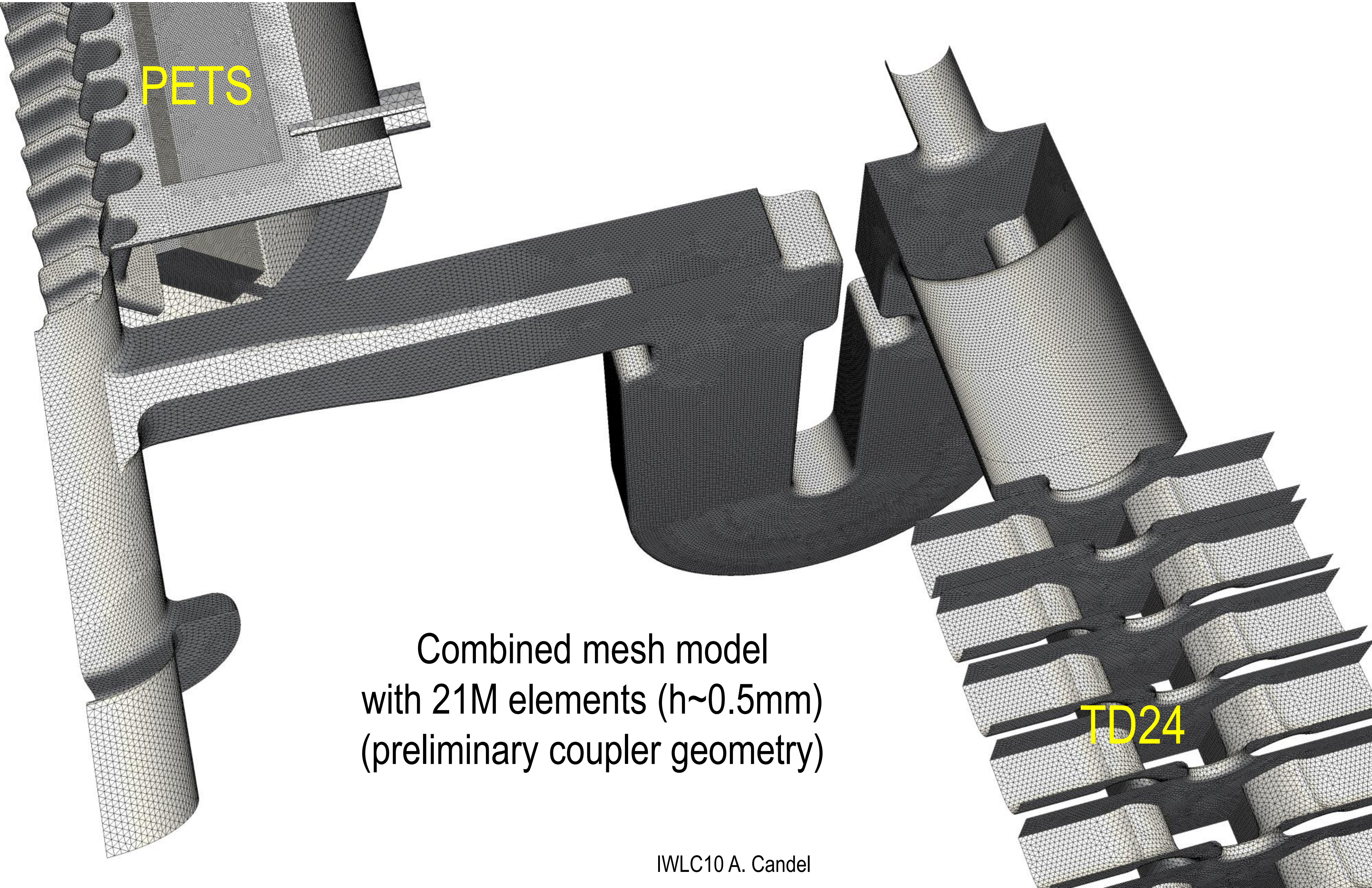
REPORT FROM THE ADVISORY PANEL ON THE PROSPECTS
FOR e^+e^- LINEAR COLLIDERS IN THE TeV RANGE

GENEVA
1987

CLIC two-beam in numbers

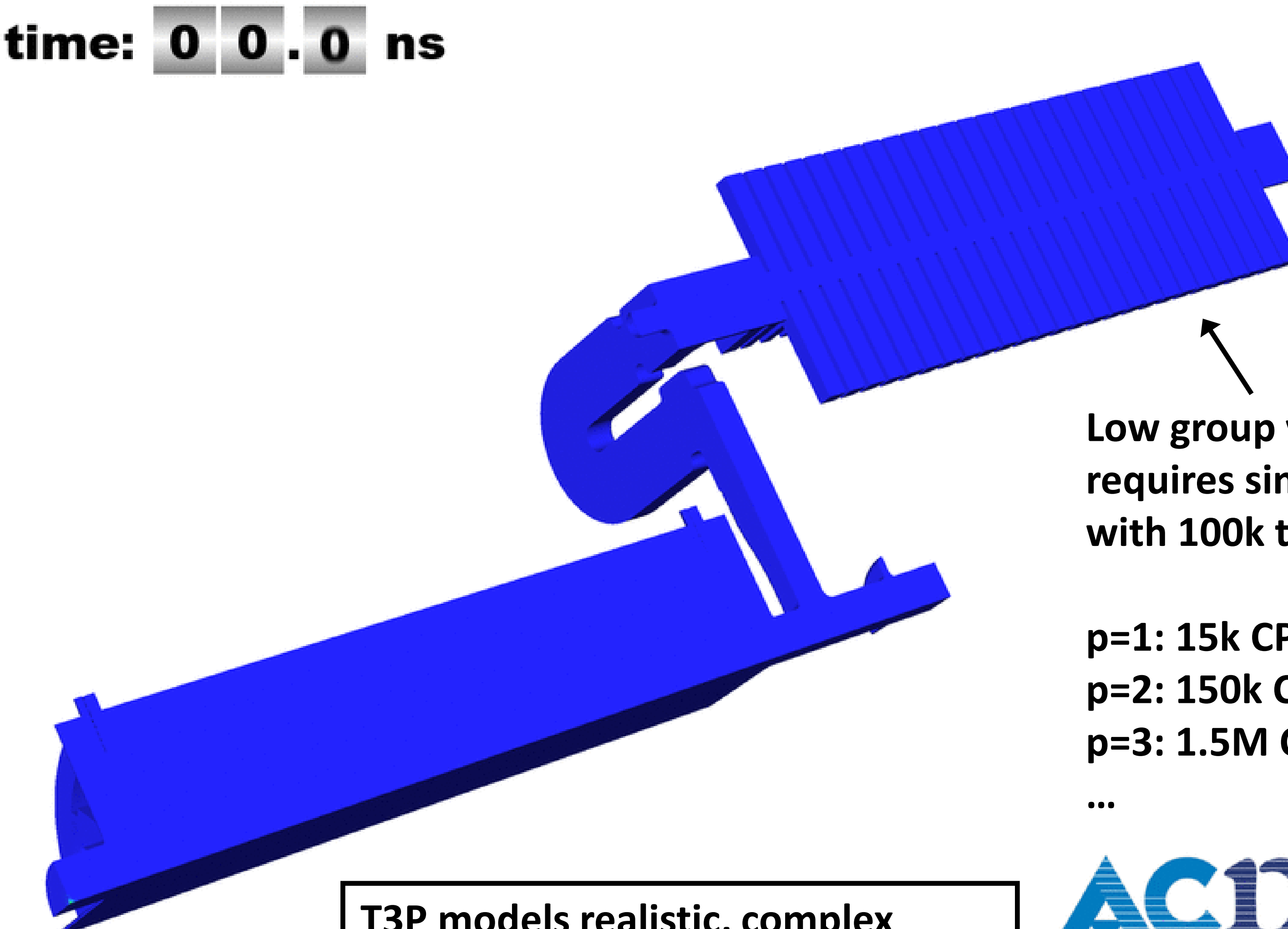
	PETS	Accelerating structure
Aperture radius [mm]	11.5	3.15-2.35
R'/Q [kΩ/m]	2.2	15-18
v_g/c	0.49	0.0165-0.0083
Gradient [MV/m]	-6.3	+100

T3P: Wakefield Coupling PETS <-> TD24



Combined mesh model
with 21M elements (h~0.5mm)
(preliminary coupler geometry)

… and Simulation of RF power transfer



Low group velocity requires simulations with 100k time steps

p=1: 15k CPU hours
p=2: 150k CPU hours
p=3: 1.5M CPU hours
…

T3P models realistic, complex accelerator structures with unprecedented accuracy

ACD
ADVANCED COMPUTATIONS

PETS – specifications

High-power:

1. 135 MW output power
2. 170 (flat top)/240 (full) ns pulse length
3. $<2x10^{-7}$ 1/pulse/m breakdown rate

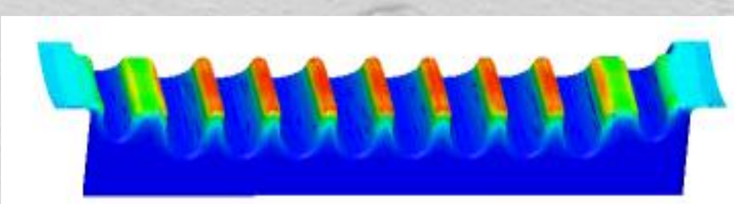
Beam dynamics:

1. Fundamental mode: gives 23 mm diameter aperture which corresponds to $a/\lambda=0.46$ and $v_g/c=0.49$ to give 2.2 kΩ/m, longitudinal impedance
2. Single bunch transverse wake: < 8 V/pC/mm/m
3. Long-range transverse wakefield with effective suppression of main HOMs by $Q_n(1-\beta_n)<8$ each

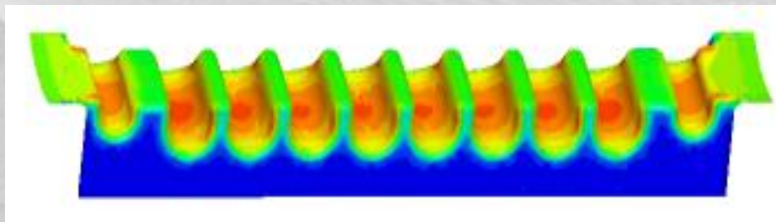
PETS parameters

Aperture, mm	23
Iris thickness. mm	2.0
Cell length, mm	6.253
Phase advance/cell, degrees	90
Corrugation depth, mm	4.283
R/Q, Ohm/m	2290
$\beta = V_g/c$	0.453
Q-factor	7200
Active length, m	0.213 (34 cells)
RF pulse length, ns	241
Drive Beam current, A	101
Output RF power, MW	133.7
Peak surface electric field, MV/m	56
Peak surface magnetic field, MA/m	0.08
Pulsed temperature rise, ^{0}C	1.8
Breakdown trip rate, 1/pulse/meter	1×10^{-7}

PETS – fundamental mode characteristics



Surface electric field



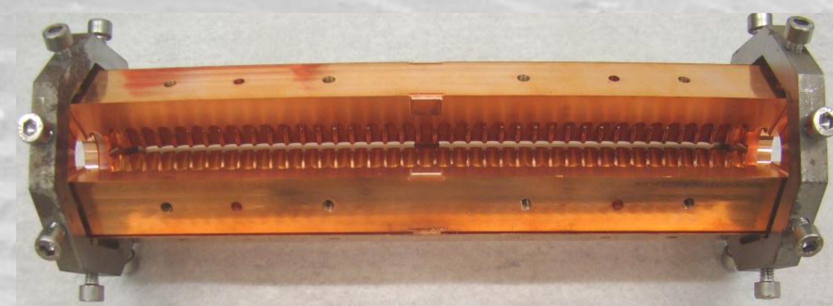
Surface magnetic field

Beam-driven structure so power rises quadratically with current and length,

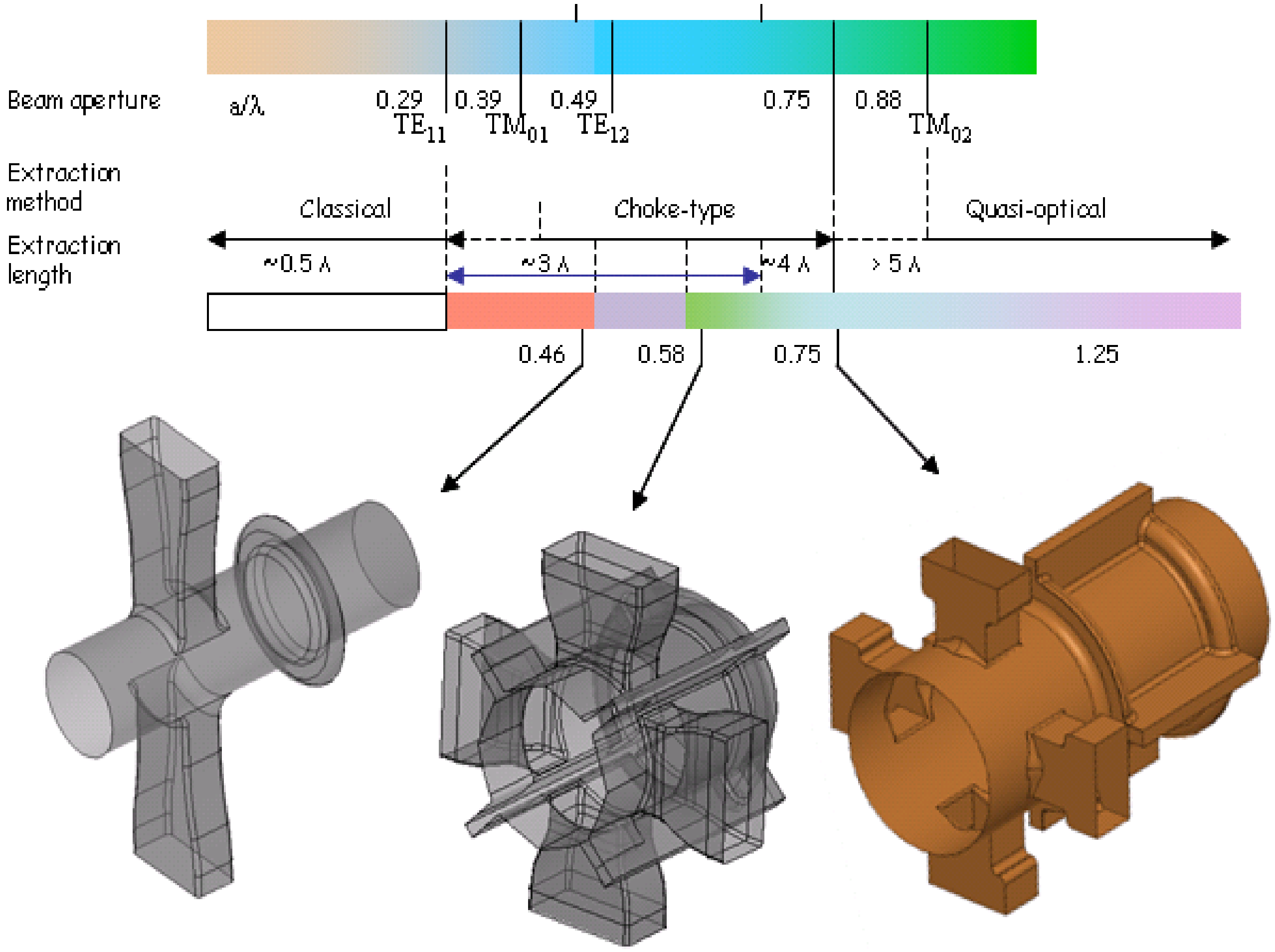
- 135 MW for 100 A beam
- 213 mm active length

Maximum fields at output with values,

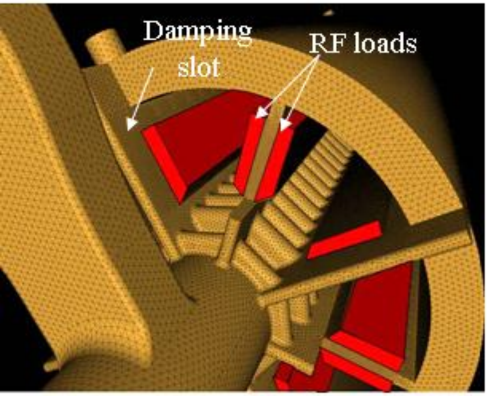
- E_{surf}=56 MV/m
- ΔT=1.8 (H_{surf}=0.08 MA/m)
- S_c=1.2 MW/mm^2

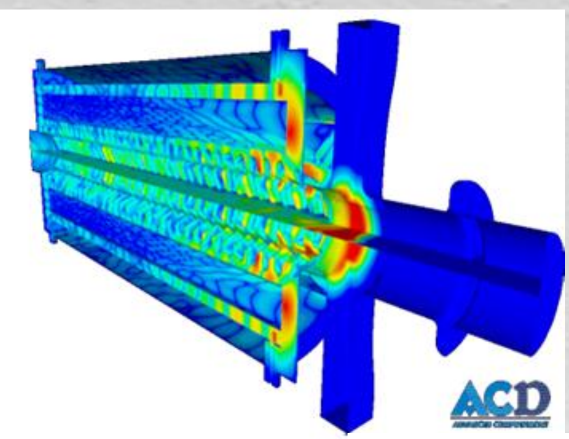


Overmoded couplers for PETS



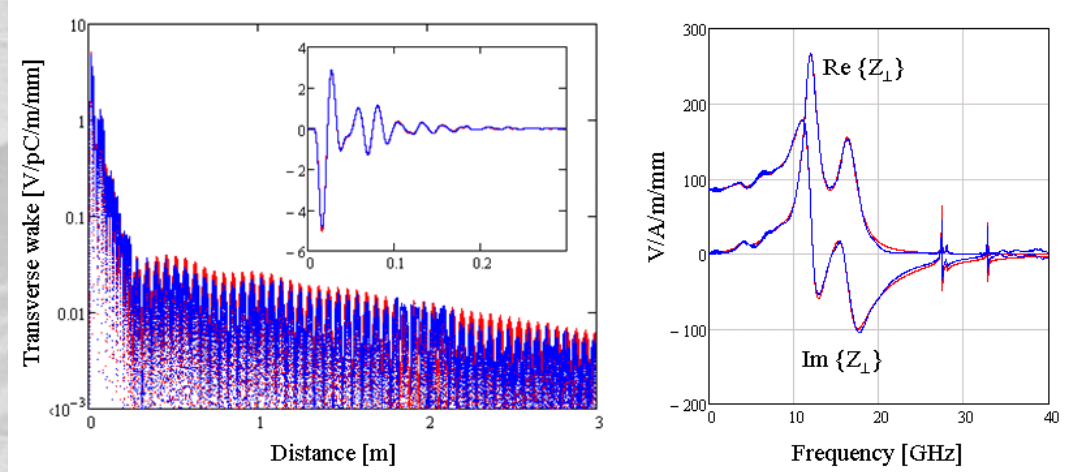
PETS – HOM suppression features

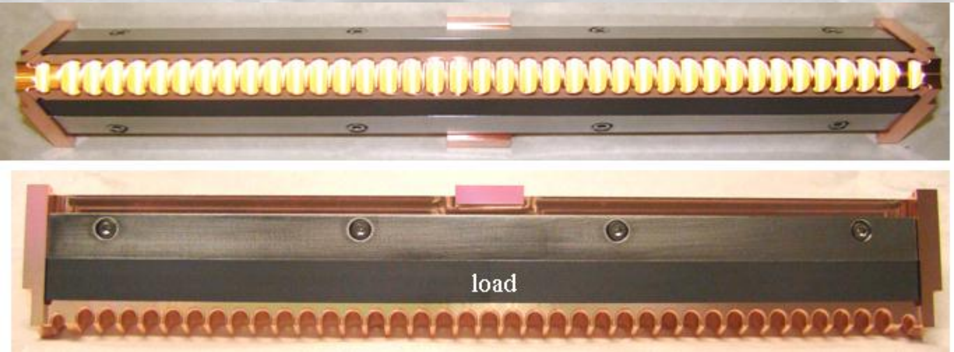


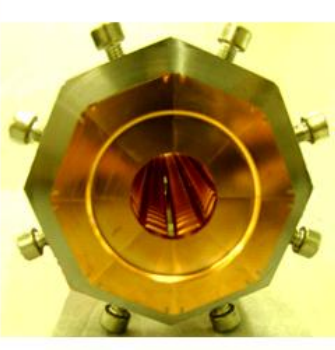


ACE3P analysis of HOM properties

GdfidL and ACE3P benchmarking with analysis of PETS HOM properties







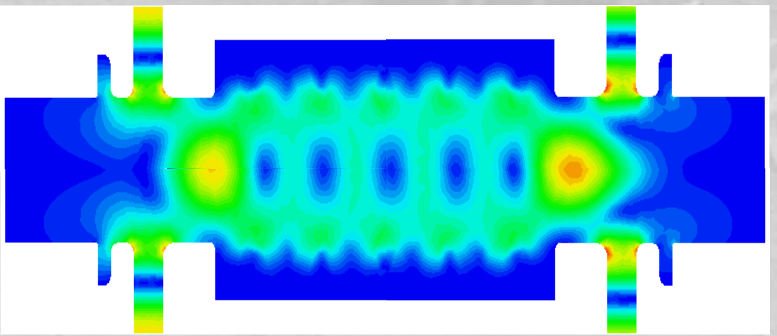
PETS for high-power testing **with SiC absorbers installed.**

PETS – the high-power testing challenge

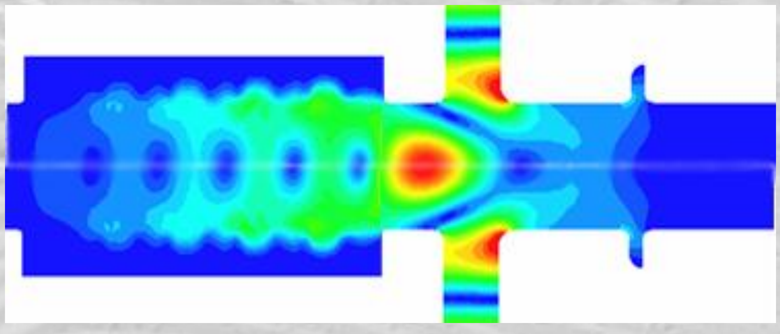
To high-power test the PETS in nominal conditions would require a 100 A driving beam.

“Waveguide” test with klystron/pulse compressor
• not many 135+ MW X-band power sources – ASTA at SLAC
• much harder to run, full fields at input

Beam-based tests with CTF3 4-30 A beam.
• 1000 mm long PETS
• Connect output to input – beam-driven rf resonant ring for lower, <10 A, current



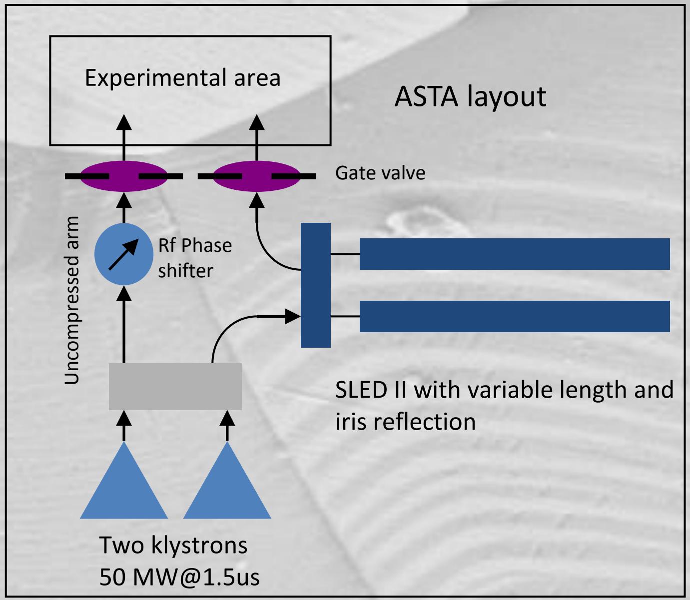
Fields in klystron and recirculation tests

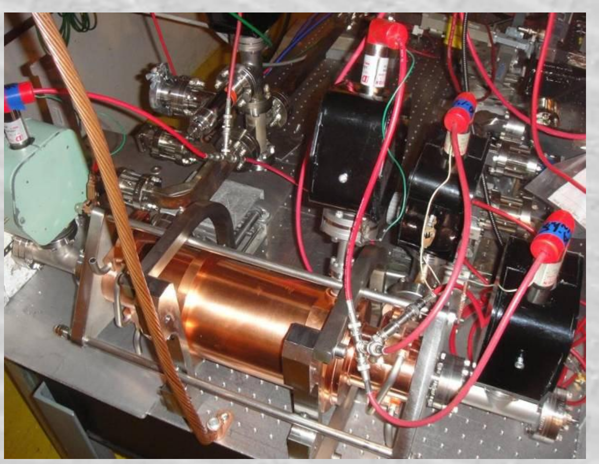


Fields in CLIC and CTF3 at high current

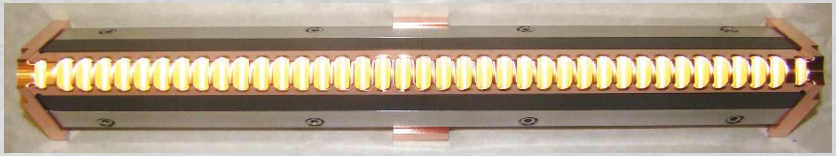
PETS testing in ASTA

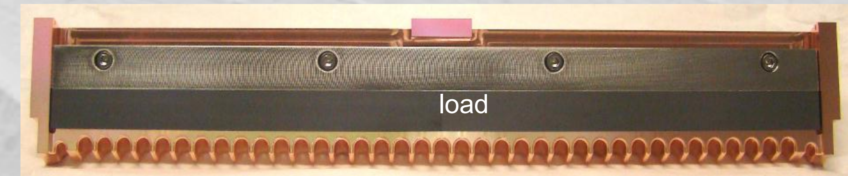
PETS waveguide-mode PETS testing is being done at ASTA in SLAC an impressive facility but testing a single object with 135+ MW power is very challenging. The results you will see are a mixture of conditioning of the PETS and ASTA…

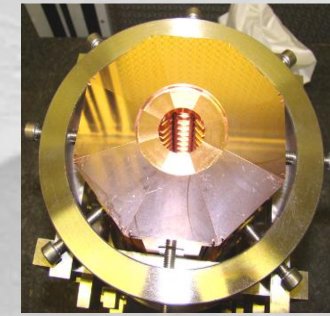




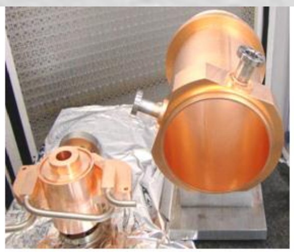
ASTA test PETS version with damping slots and **damping material (SiC)**

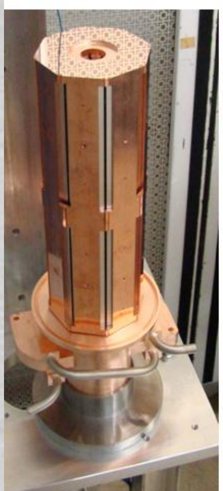


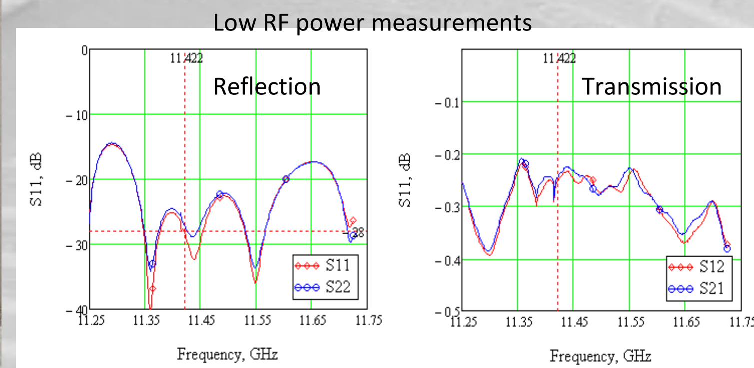




PETS preparation for the EB welding of the RF couplers and the mini-tank

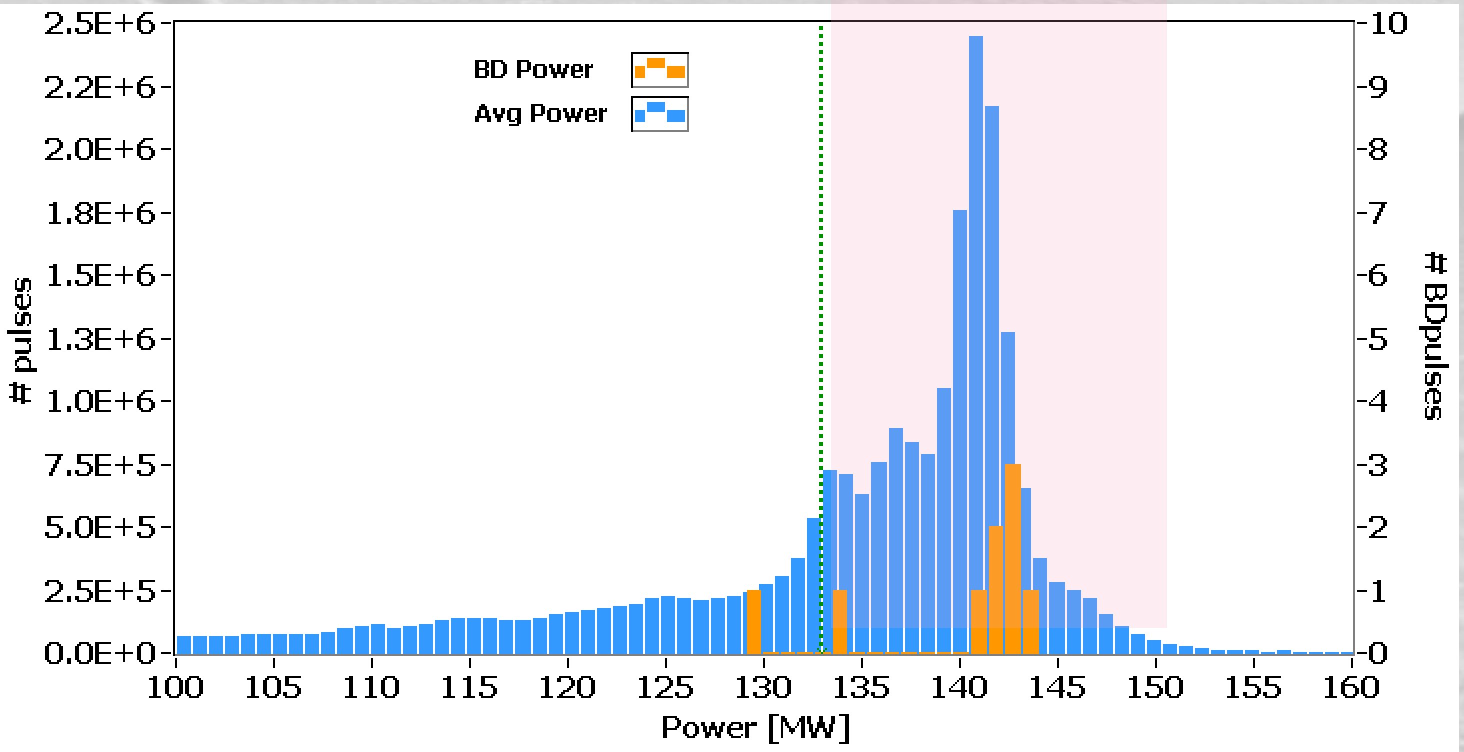






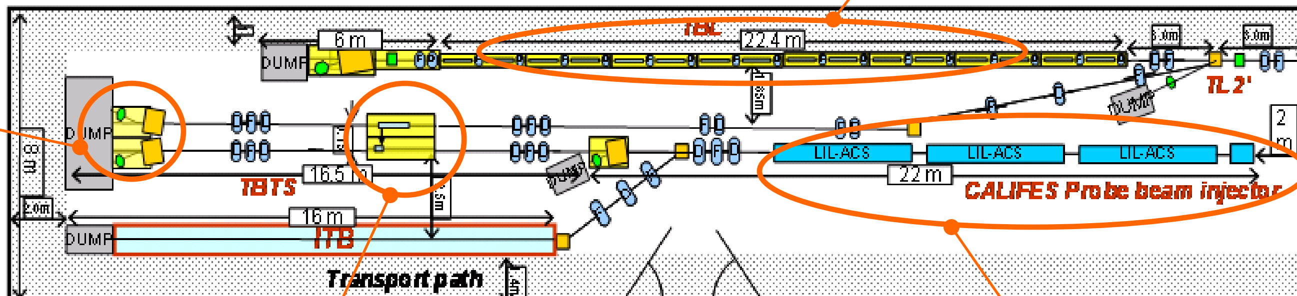
Extraction of PETS breakdown trip rate

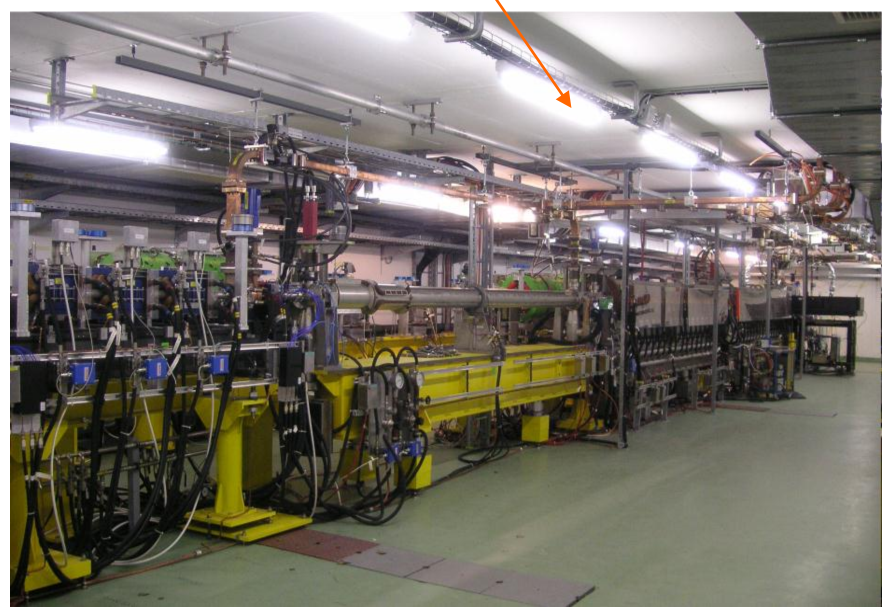
Part of the statistical distribution → 1.55×10^7 pulses



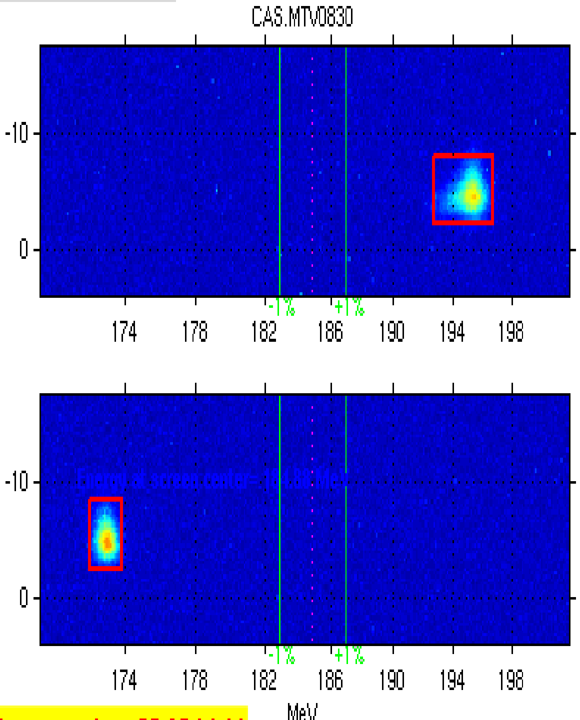
- 1.55×10^7 pulses were accumulated in a 125 hour run.
- 8 PETS breakdowns were identified giving a breakdown rate of **5.3×10^{-7}/pulse**.
- Most of the breakdowns were located in the upper tail of the distribution, which makes BDR estimate rather conservative.
- During the last 80 hours no breakdowns were registered giving a BDR **<1.2×10^{-7}/pulse**.

TBTS is the test area in CLEX, where feasibility of the CLIC two beam acceleration scheme is…already demonstrated (not yet at a nominal 100 MV/m accelerating gradient).

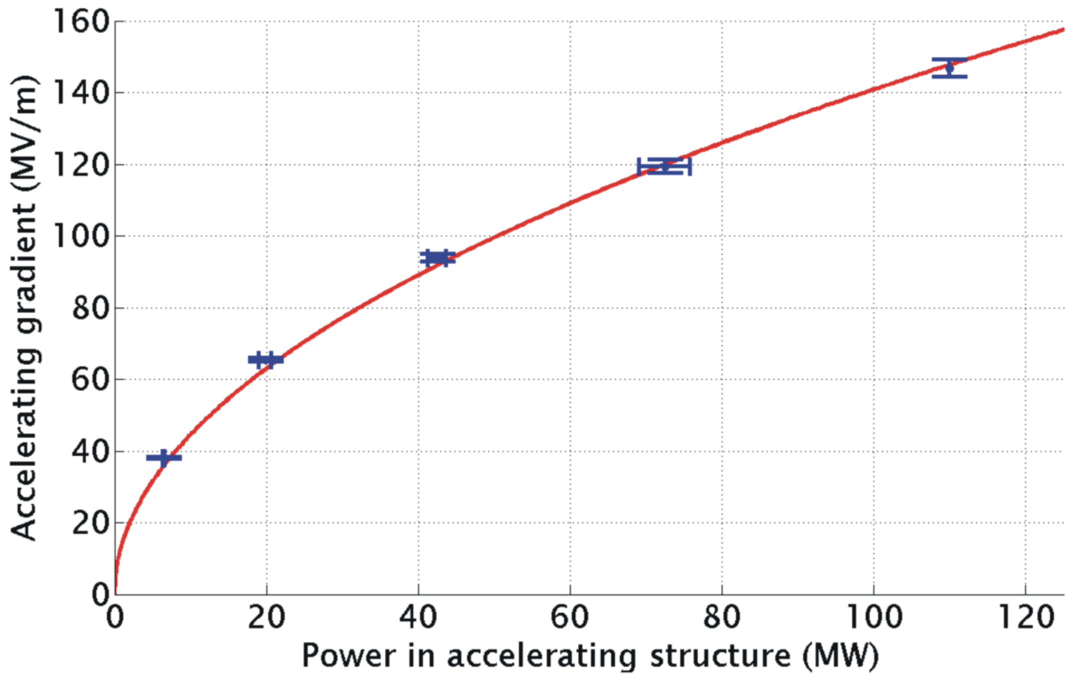




TBTS: Two Beam Acceleration



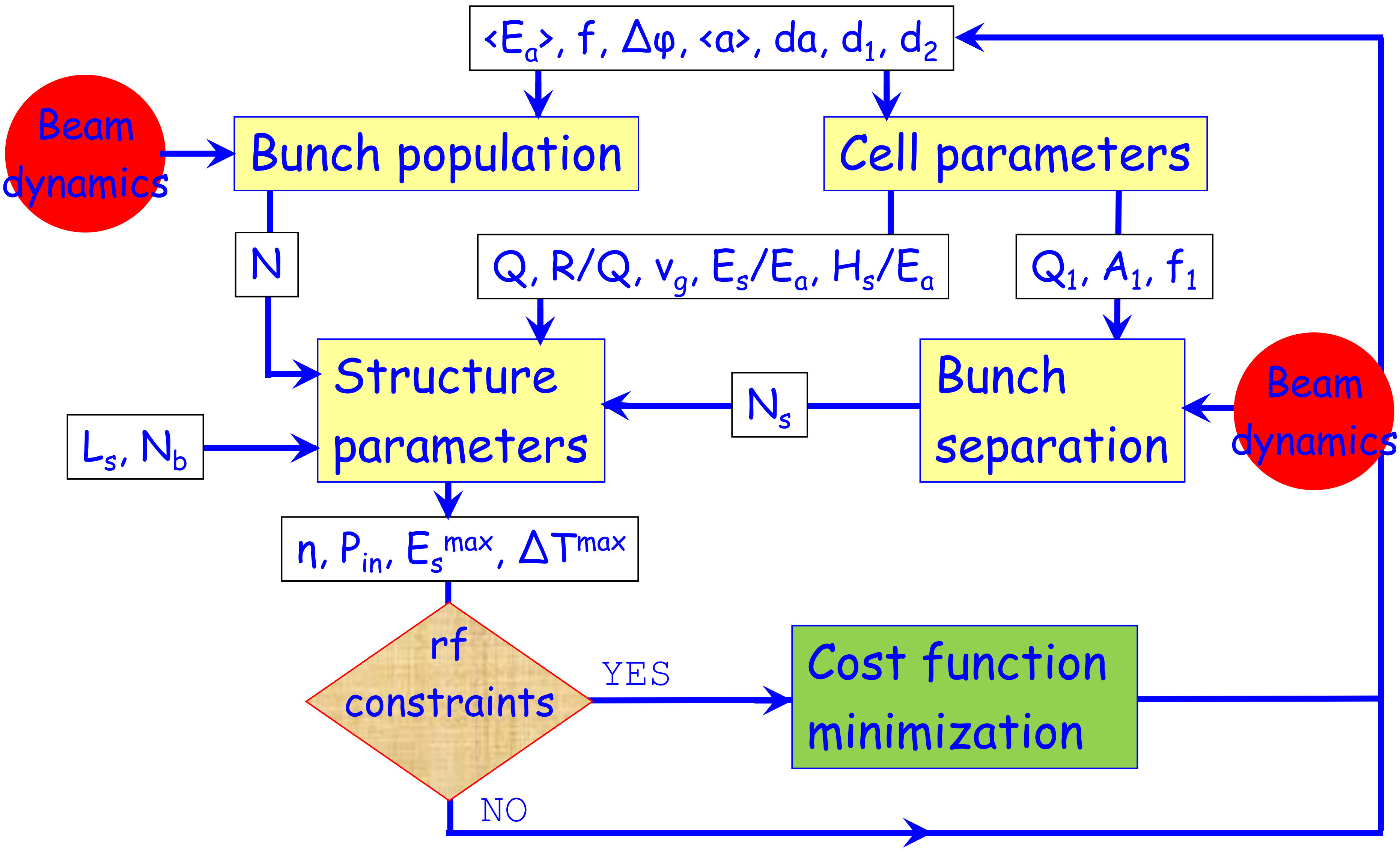
Energy gain = 23.08 MeV



Maximum gradient 145 MV/m

Consistency between
- produced power
- drive beam current
- test beam acceleration

Optimization procedure



Beam dynamics input

$$FoM = L_{bx}/N \cdot \eta$$

BD → L_{bx}/N

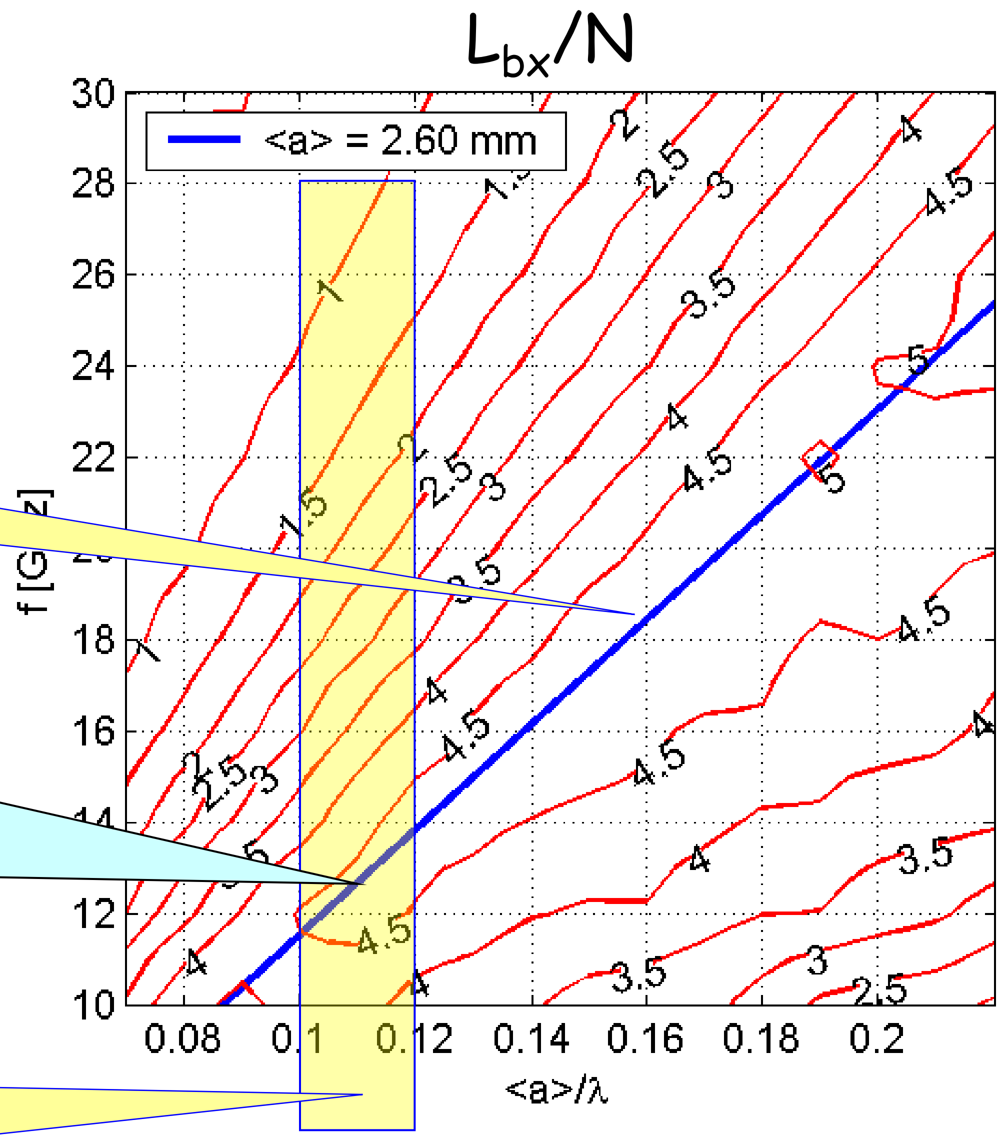
RF → η

BD optimum aperture:
<a> = 2.6 mm

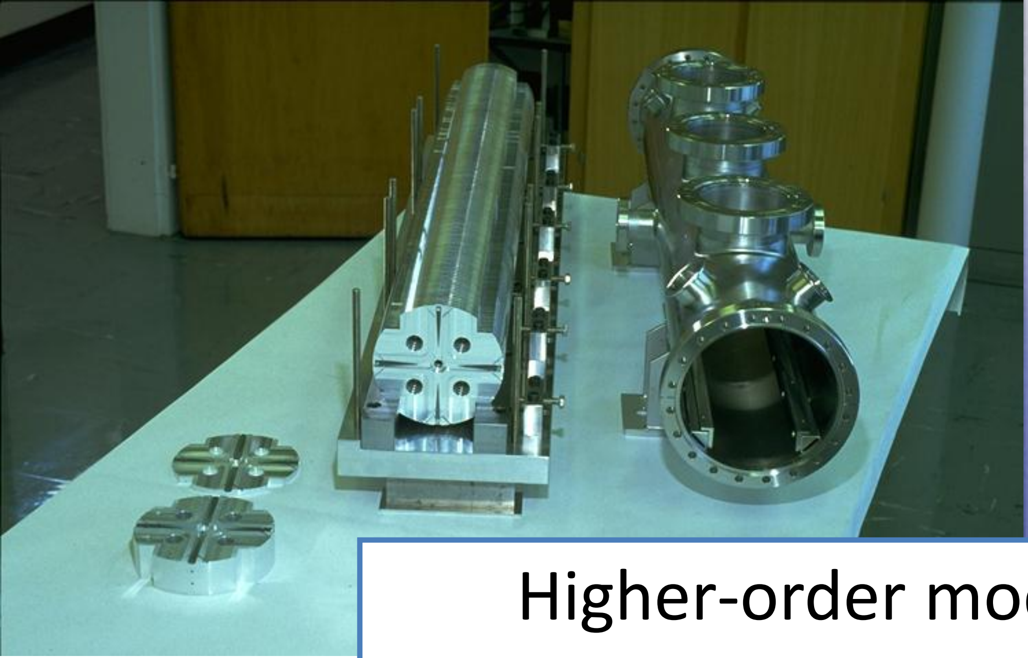
Why X-band ?

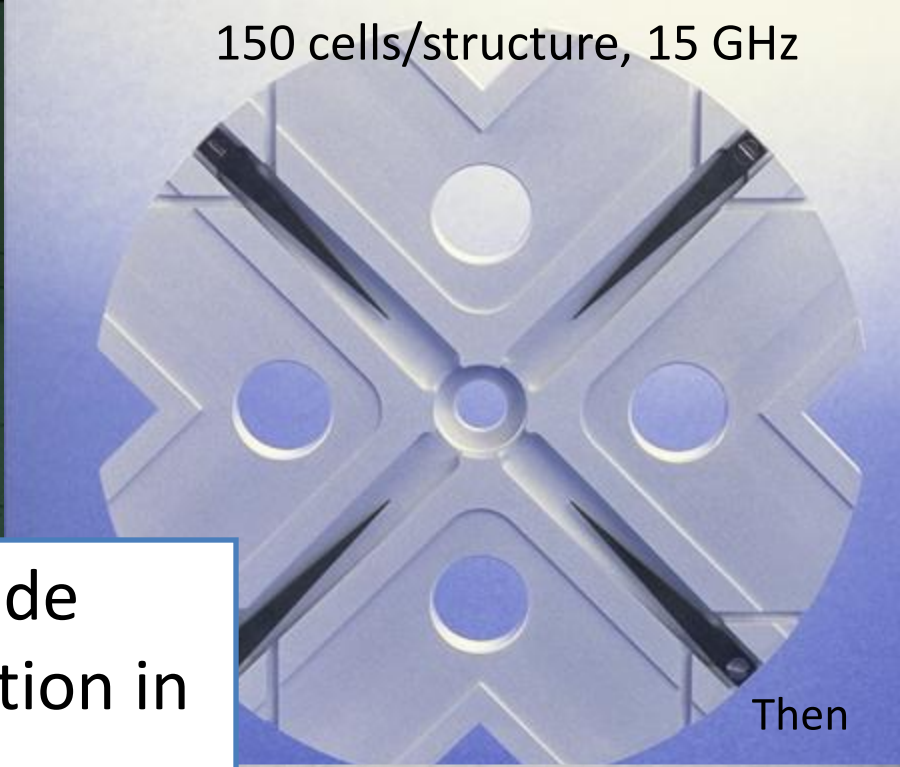
Crossing gives optimum frequency

High-power RF optimum aperture: <a>/λ = 0.1 ÷ 0.12



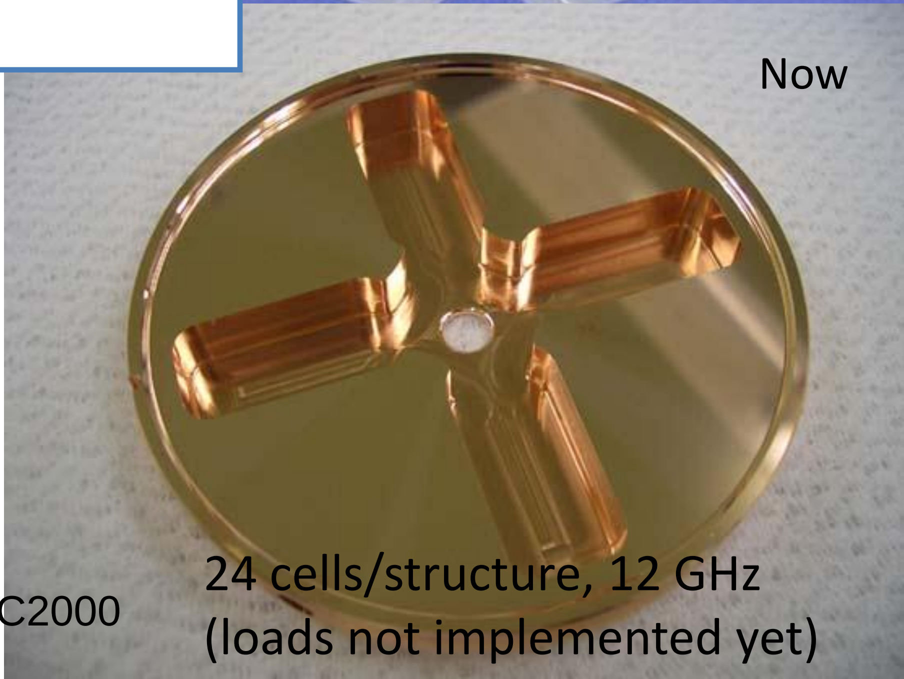
Higher-order mode damping demonstration in ASSET





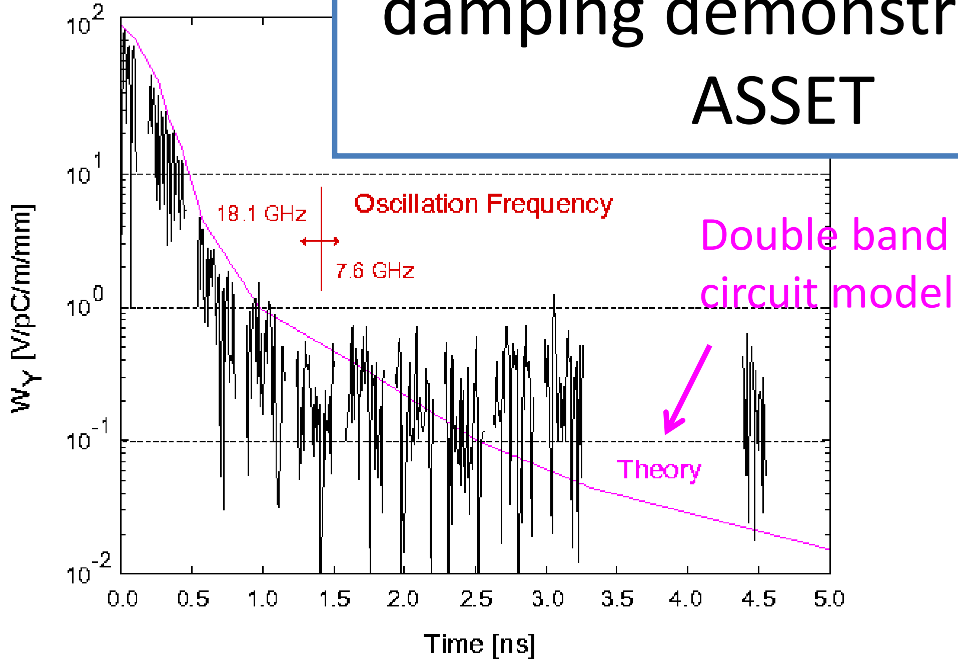
150 cells/structure, 15 GHz

Then



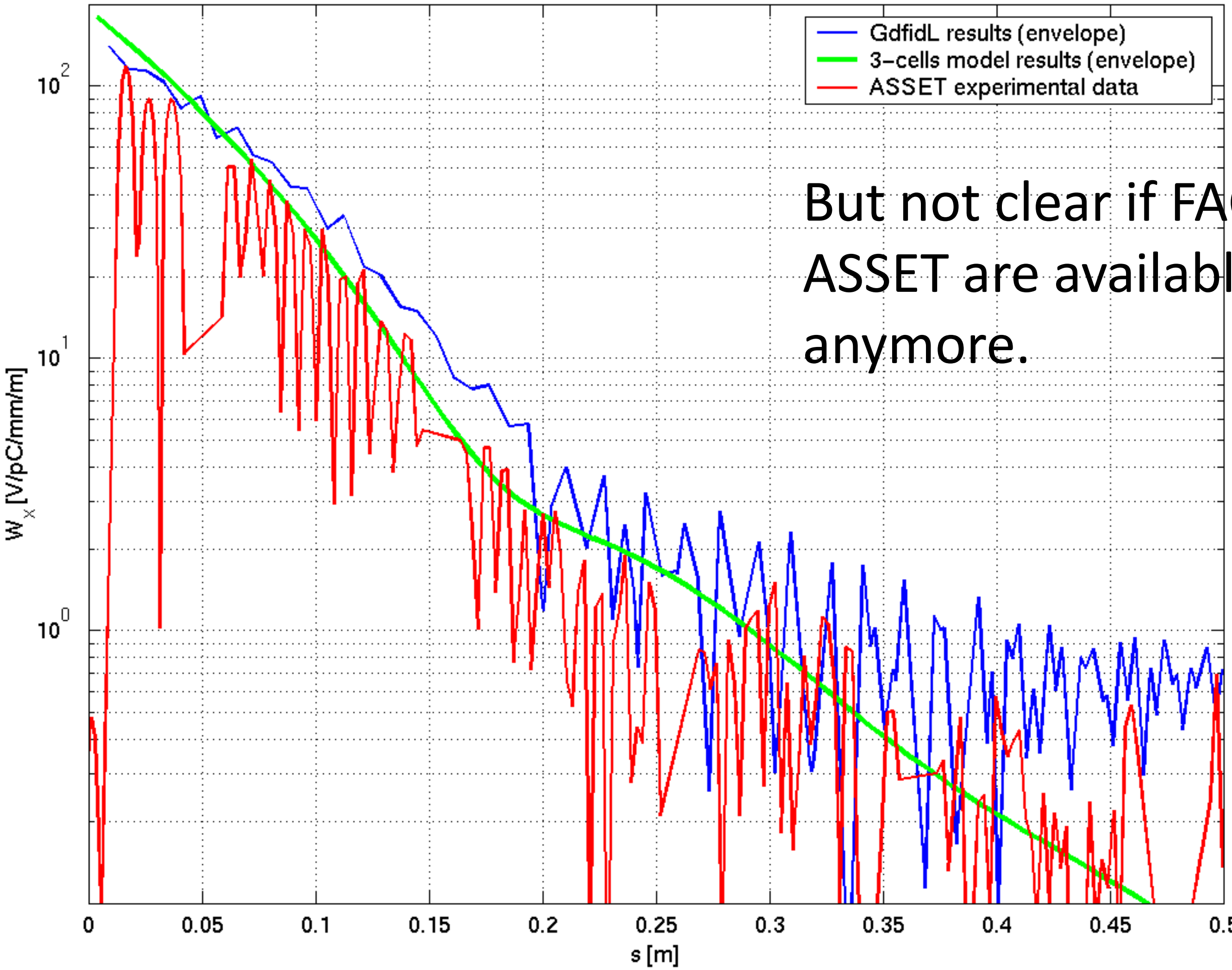
Now

24 cells/structure, 12 GHz
(loads not implemented yet)



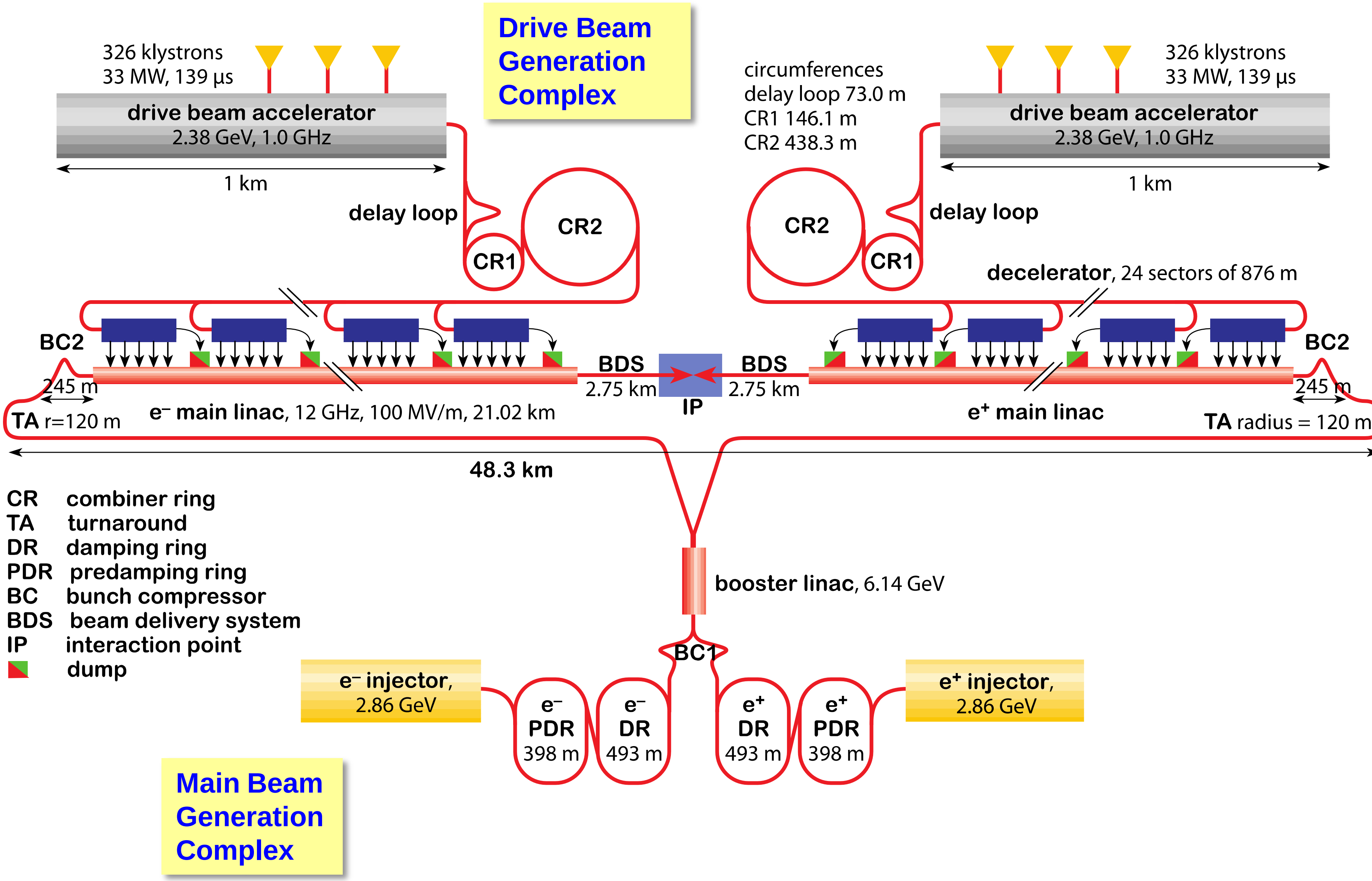
An Asset Test of the CLIC Accelerating Structure, PAC2000

Full length TDS results comparison



But not clear if FACET or ASSET are available anymore.

The CLIC Layout



More information:

CLIC: http://clic-study.org/
Linear collider workshop:
http://www.uta.edu/physics/lcws12/pages/registration.html
Breakdown physics:
http://www.regonline.com/builder/site/Default.aspx?EventID=1065351
High-gradient structures:
https://indico.cern.ch/conferenceDisplay.py?confId=165513