Key technology developments for the CLIC accelerator

CERN academic training

8 March 2018

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Disclaimer

The CLIC study makes use of many current and new technologies all of whom would be very difficult to fit in 55 minutes.

I have chosen to show you the technologies that have been mostly developed for CLIC:

- either exclusively,
- or in their most challenging form

Whenever possible I will try to explain the original requirements coming from CLIC performance.

RF technologies

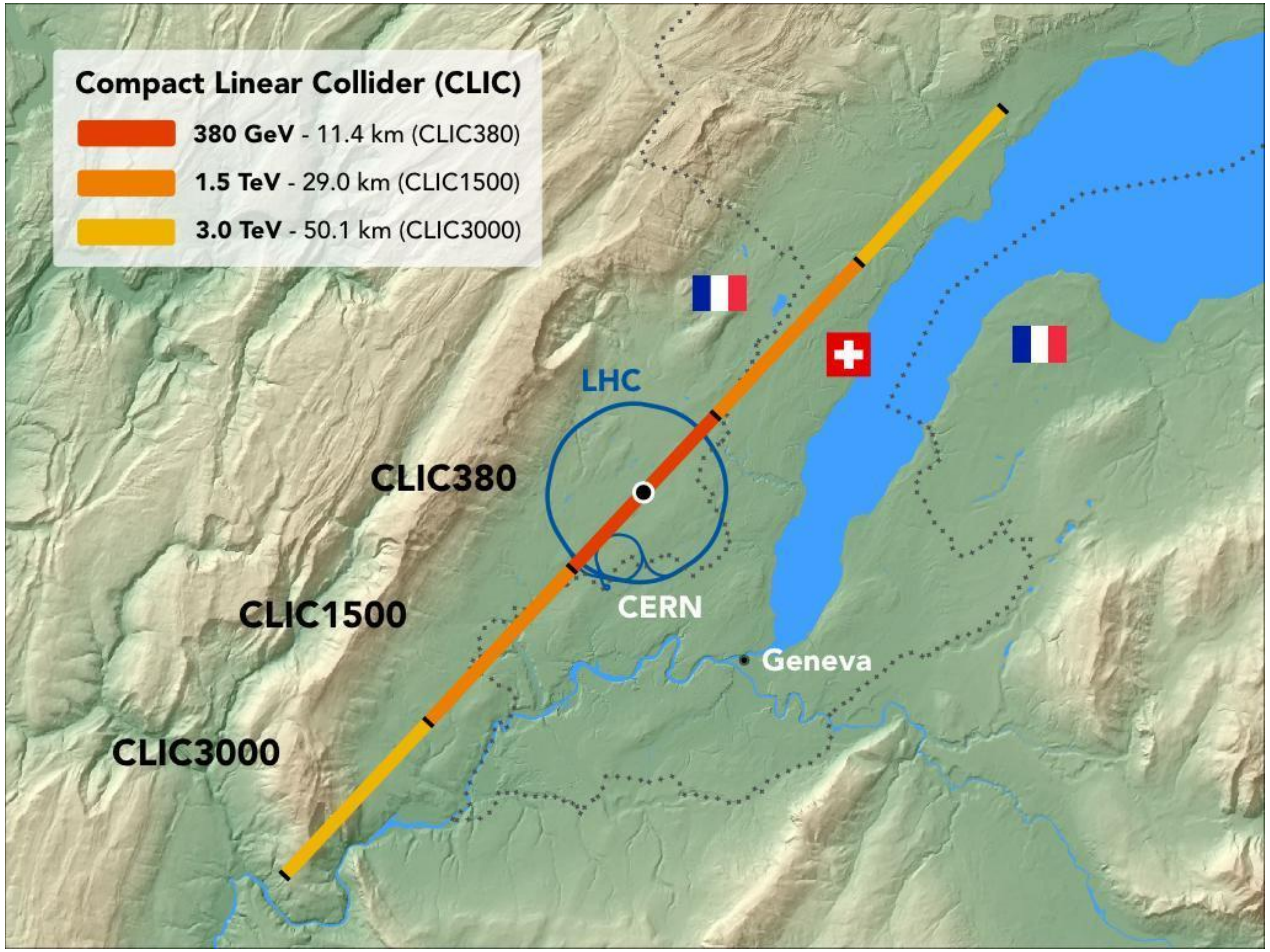
http://www.linearcollider.org/school/2016

Principles RF Linear Accelerators. Thomas P. Wangler

CLIC Conceptual Design Report

CLIC RF Technology choice

- Energy (3TeV) and luminosity (>10^{-34}) define the physics case of a collider
- CLIC stands for Compact LInear Collider
  - 3TeV collider > 50km!
  - Aim at ~100MV/m
- Superconducting cavities have lower gradient (fundamental limit) with long RF pulse
  - Eacc<50 MV/m limited by field emission and peak magnetic fields that produce quenches
- Normal conducting cavities allow for higher gradient with shorter RF pulse length
  - Also limited by field emission and magnetic field through pulse heating but Eacc > 50 MV/m



CLIC RF Pulse length

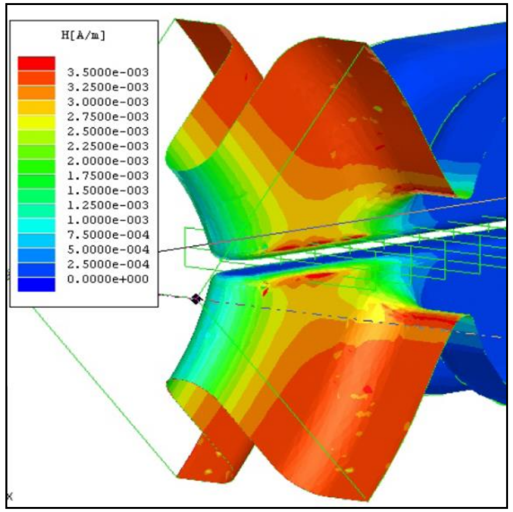
- Pulsed surface heating leads to material fatigue and is proportional to square root of pulse length and square of peak magnetic field
- Pulse surface heating also limits operation due to vacuum arcs
- Field reduced by geometry, but high field still needed for high gradient

$$\Delta T = \sqrt{\frac{\mu_0}{2\pi}\frac{\omega t_P}{\sigma \lambda \rho c_H}}\hat{H}^2$$

ΔT temperature rise, σ electric conductivity
λ heat conductivity, ρ mass density
c_H specific heat, t_P pulse length
$\hat{H}$ peak magnetic field

$$\hat{H} = \frac{g_H}{377\,\Omega} E_{acc}$$

g_H geometry factor of structure design
typical value $g_H \approx 1.2$



Numerical values for copper

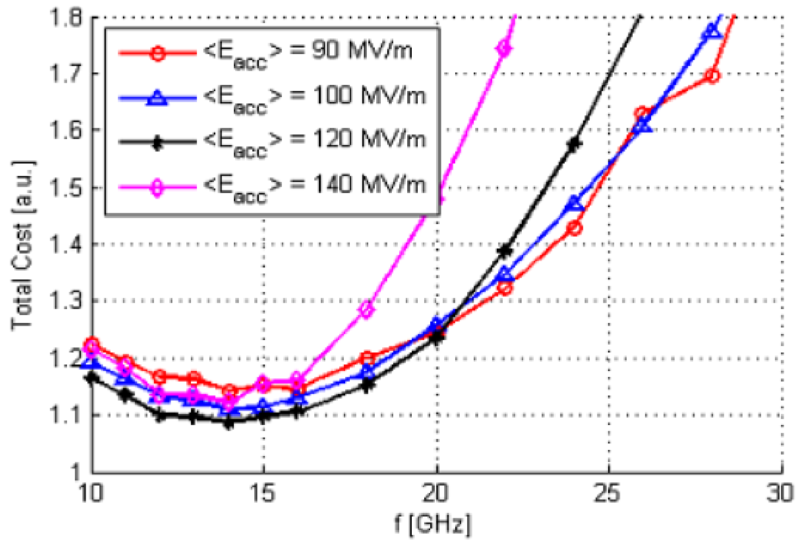
$$\Delta T \approx 4\cdot 10^{-17}\left[\frac{\mathrm{K\,m^2}}{\mathrm{V^2}}\right]\sqrt{t_P\, f}\; E_{acc}^2$$

$$\Delta T_{\max} \approx 50\,\mathrm{K}$$

$$t_P < \left(\frac{\Delta T_{\max}}{4\cdot 10^{-17}}\right)^2 \frac{1}{f\, E_{acc}^4}$$

Limits the maximum pulse length => short pulses (~few 100ns)

CLIC RF frequency



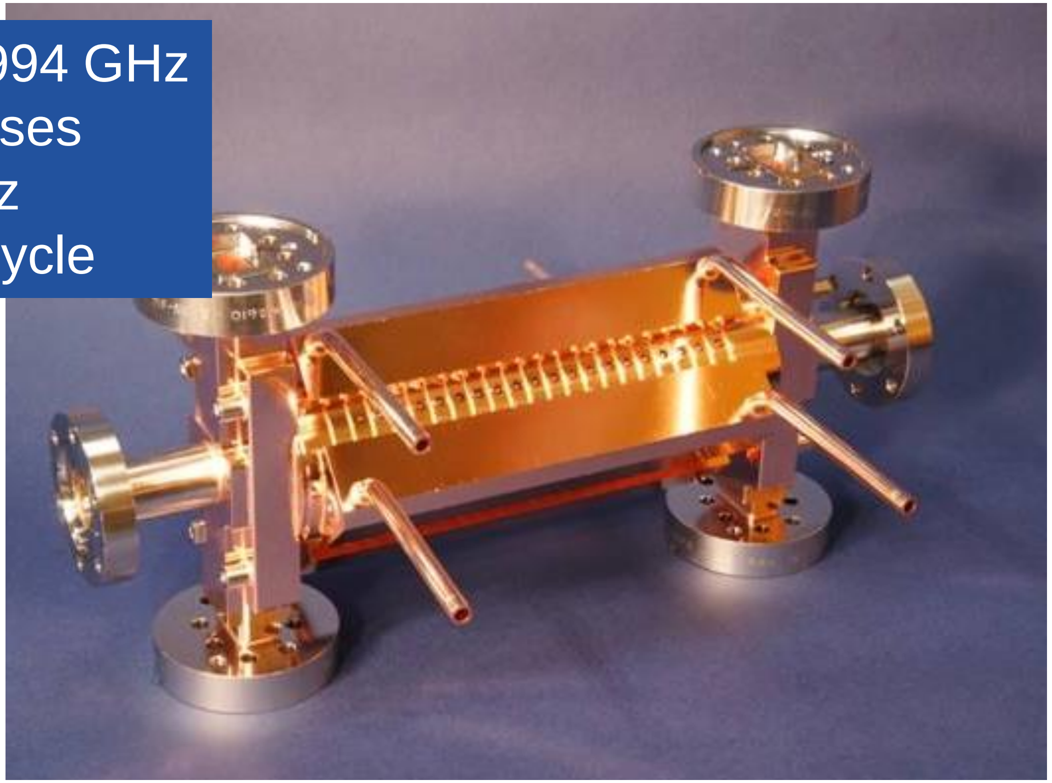
Higher frequency brings higher gradient, lower dimensions and less input power to the structures

Small dimensions also bring smaller aperture and higher wake-fields

Frequency choice based also on available technology

Frequency 11.994 GHz
~200ns pulses
@ 50 Hz
10-5 duty cycle

	380 GeV	3TeV
Length [cm]	27	24
Gradient [MV/m]	72	100
Input power [MW]	59.5	61.3
Number of structures	20600	140000
Total peak power [TW]	1.6	8.5

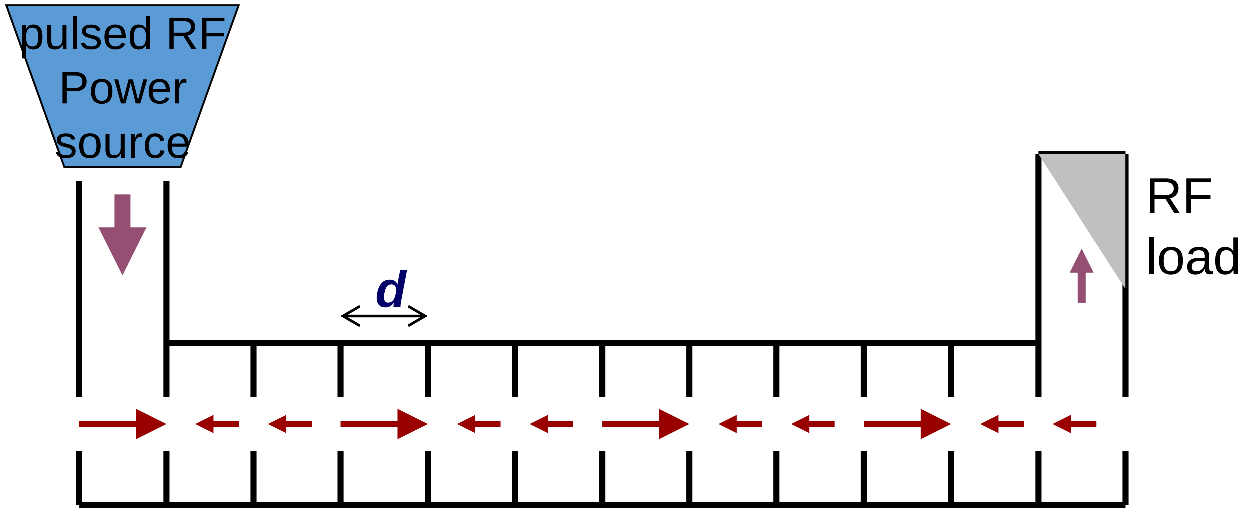


Travelling wave structures

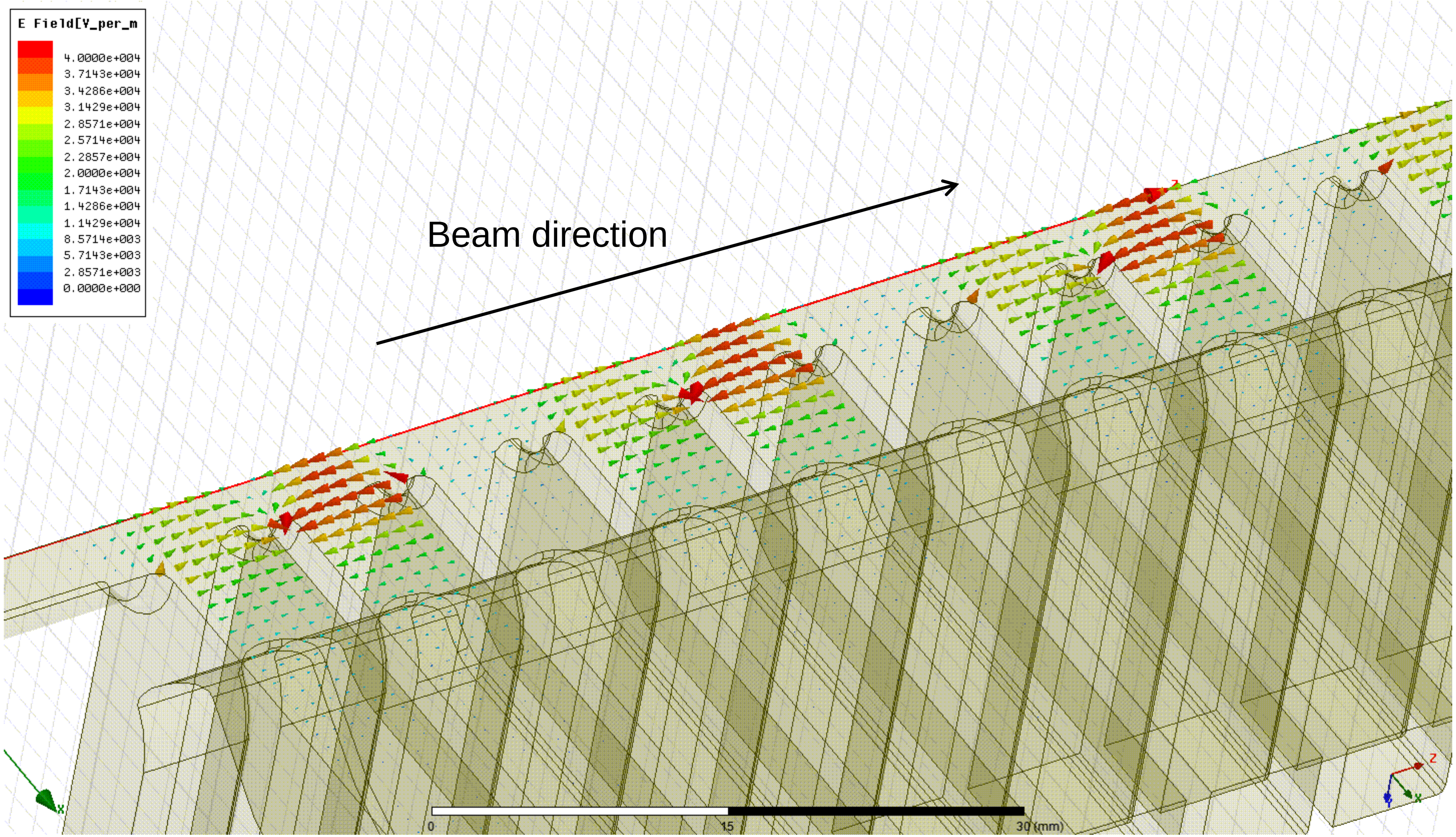
- NC standing wave structures would have high Ohmic losses and long filling time
- => travelling wave structures. Basically a cylindrical waveguide on which we have added some obstacles to slow down the phase velocity bellow the speed of light to synchronize with the beam.

$$\omega = \frac{2.405c}{b}\sqrt{1 + \kappa\left(1 - \cos\left(k_z L\right) e^{-\alpha h}\right)}$$

$$\kappa = \frac{4a^3}{3\pi J_1^2(2.405) b^2 L} \ll 1 \quad \text{and} \quad \alpha \approx \frac{2.405}{a}.$$

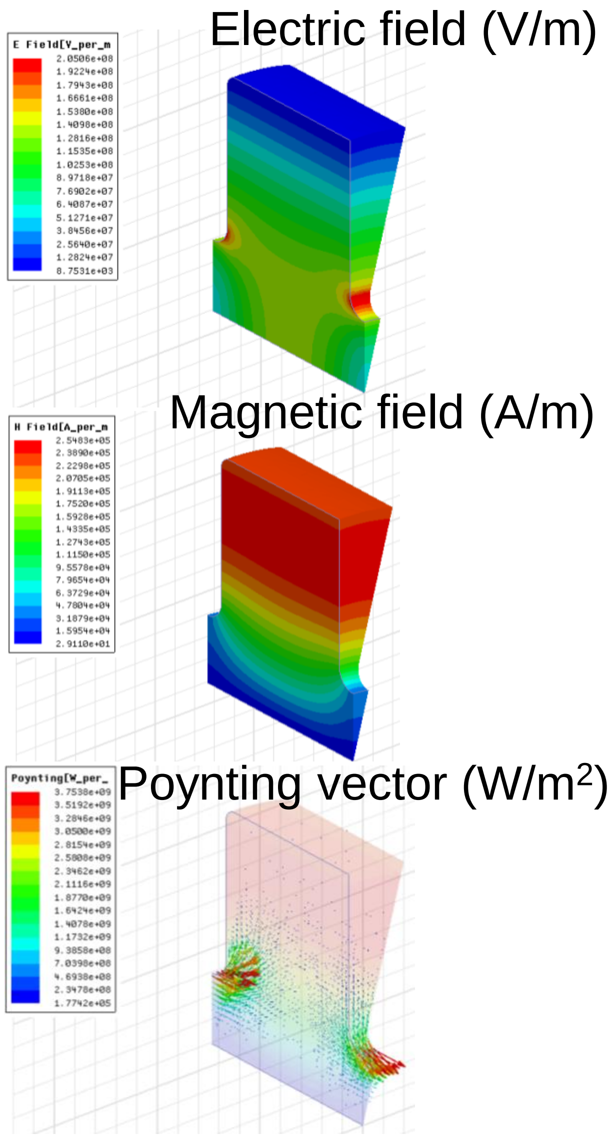


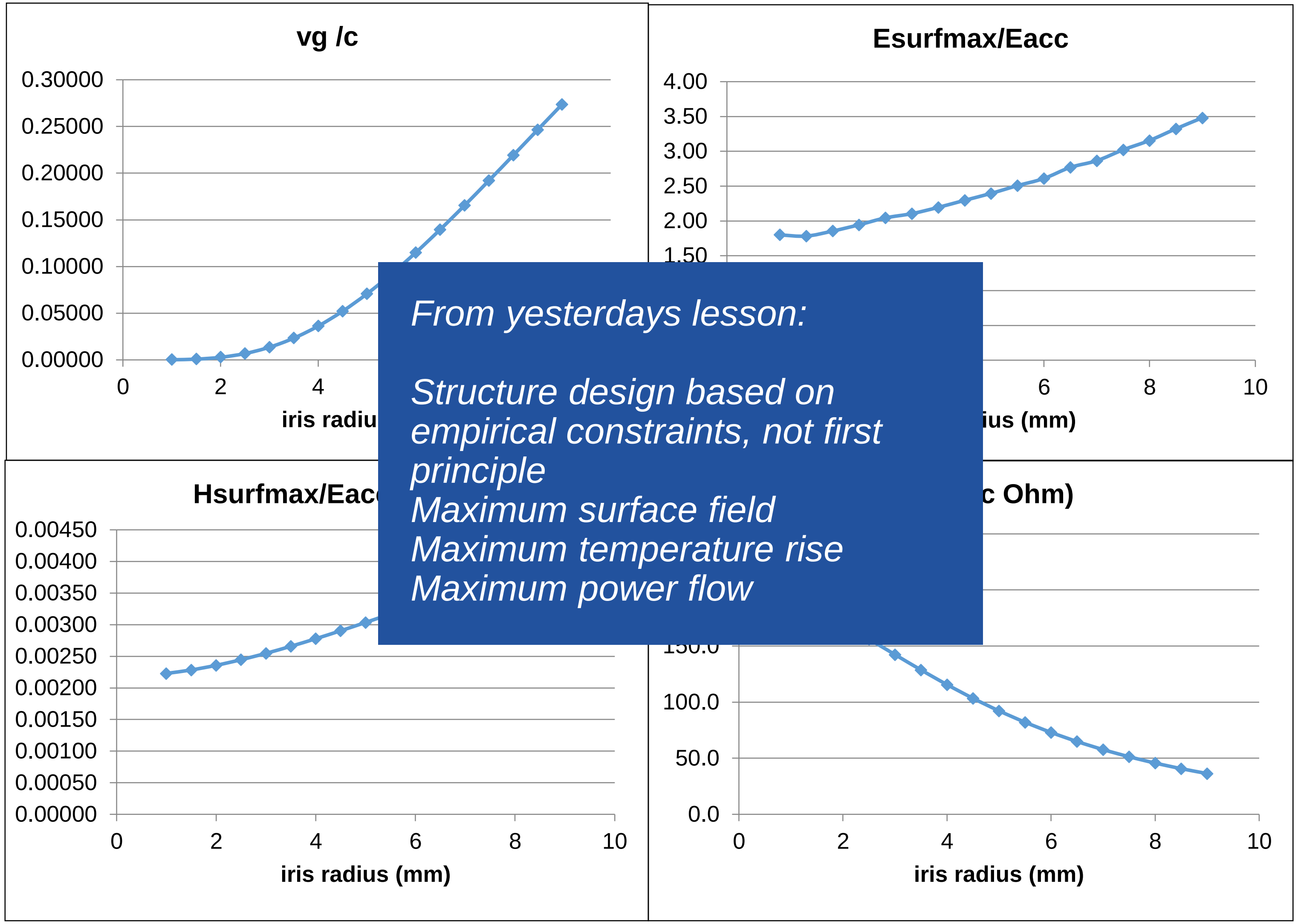
- RF 'flows' with group velocity v_G along the structure into a load at the structure exit
- Condition for acceleration: Δφ=d·ω/c (Δφ cell phase difference)
- Shorter fill time - order <100 ns compared to ~ms for standing wave



By Alexej Grudiev

Accelerating structure optimization



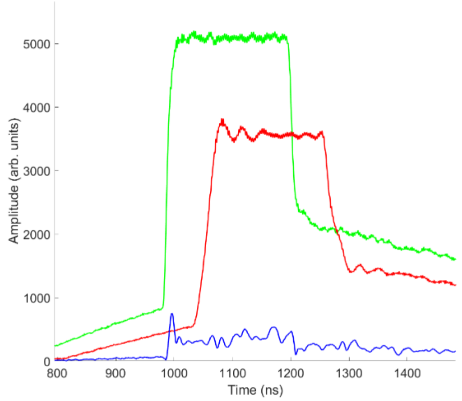


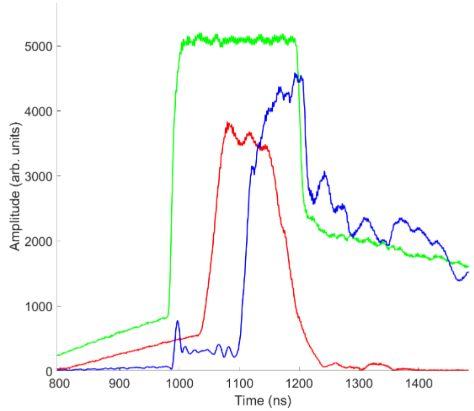
From yesterdays lesson:

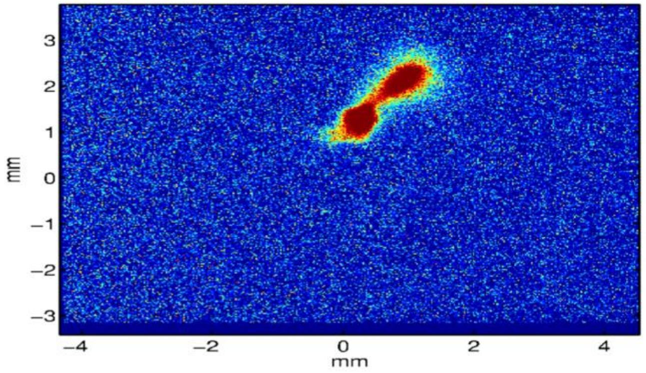
Structure design based on empirical constraints, not first principle
Maximum surface field
Maximum temperature rise
Maximum power flow

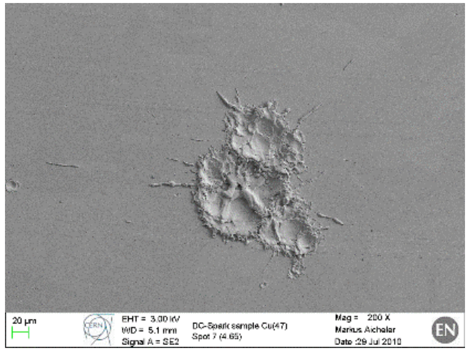
Breakdown and Conditioning

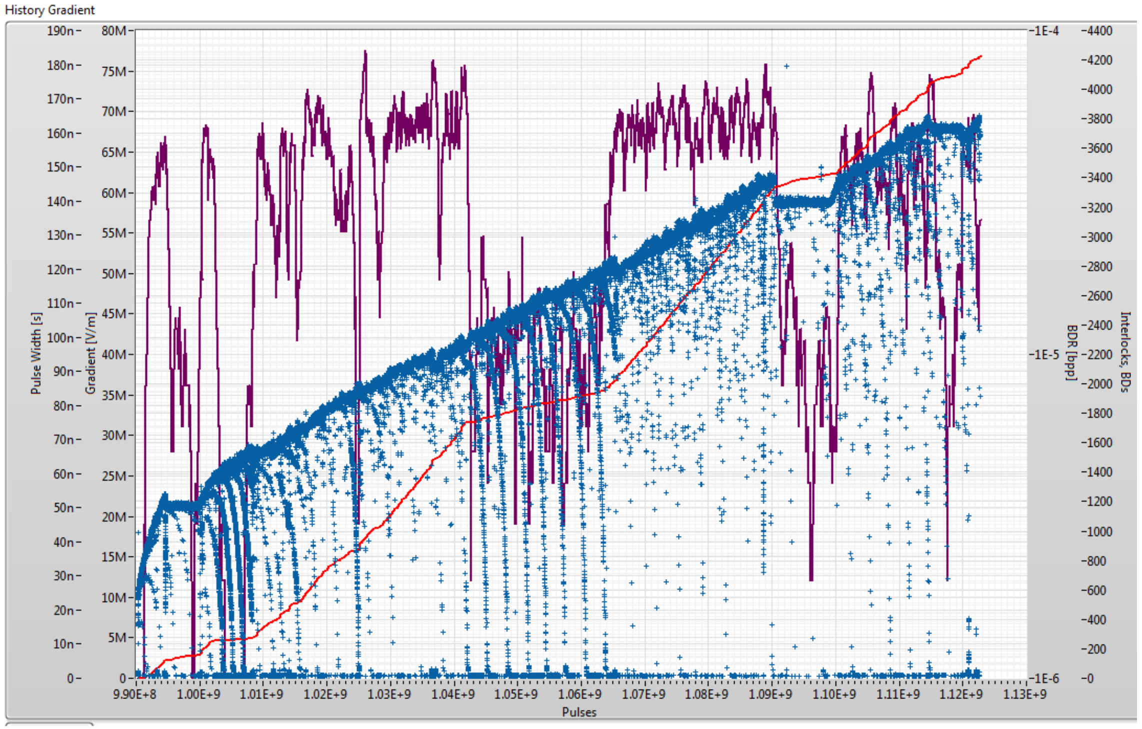
- Very high fields provoke arcing in vacuum and structure damage
- Accelerating structures do not run right away at full specification – pulse length and gradient need to be gradually increased in a process known as conditioning.











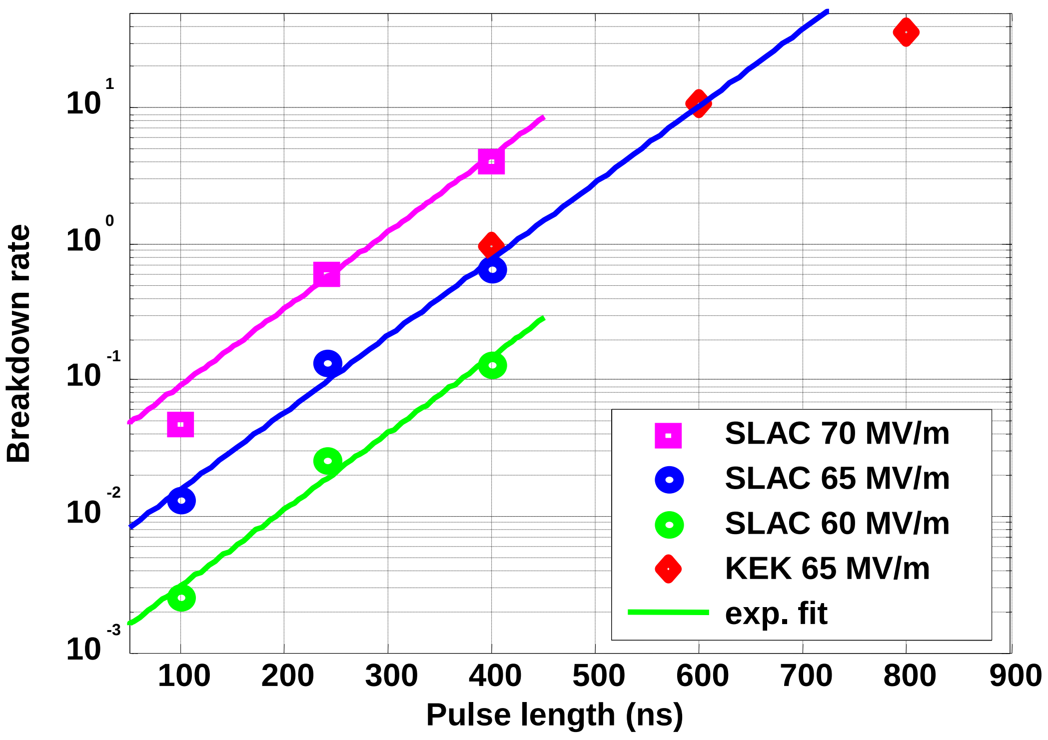
Accelerating structure specs I

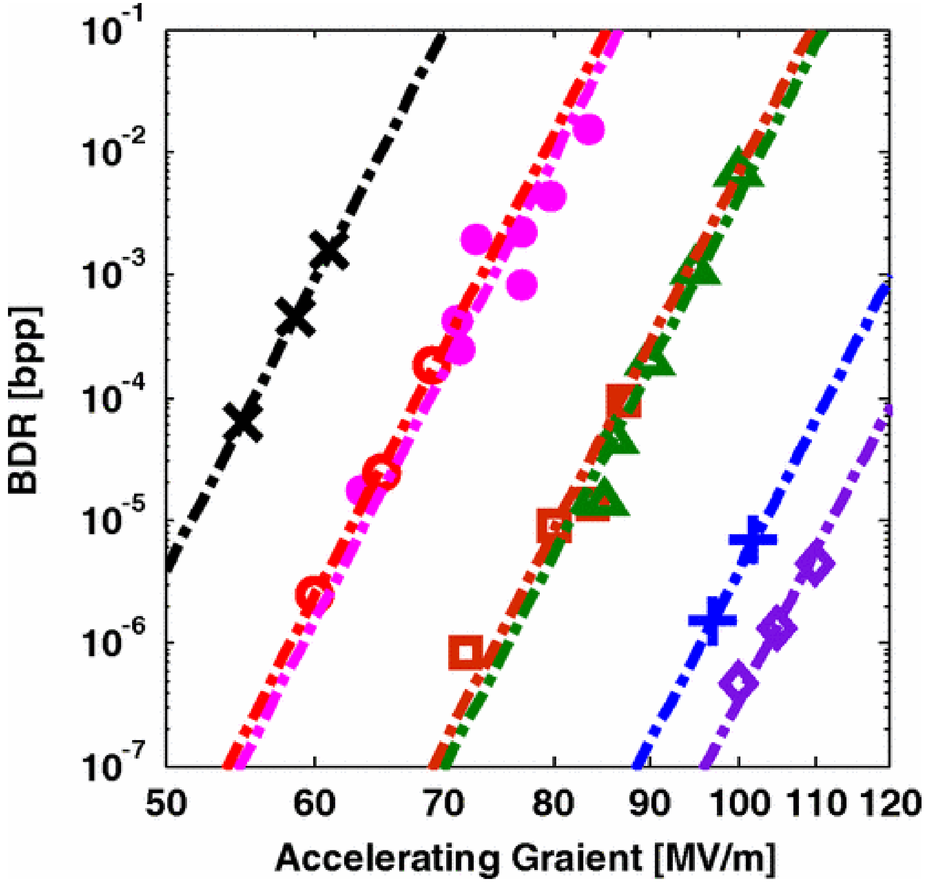
Power and gradient:

1. 100 MV/m loaded gradient
2. **Less than 3x10^{-7} breakdowns/pulse/m**
3. 240 (full) ns pulse length. 156 ns flat top

[Phys. Rev. Spec. Top. Accel. Beams 12 (2009) 102001]

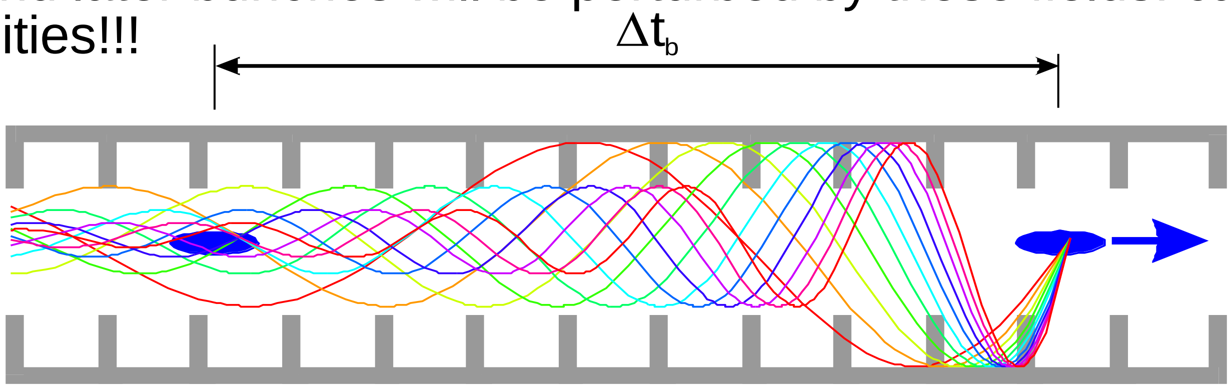
$$BDR \propto E^{30}\,\tau^{5}$$





RF structures: transverse wakefields

- A bunch will leave behind an electromagnetic field at every beam pipe geometry change called wake-field
- A waveguide is a broadband device so we can expect all frequencies to be present and specially high frequencies with a relatively high Q (“slow” damping time)
- The same bunch and later bunches will be perturbed by these fields: can lead to emittance growth and instabilities!!!



- Long and short range. Transverse and longitudinal wake-fields
- Effect depends on *a/λ* (*a* iris aperture) and structure design details
- transverse wake-fields roughly scale as $W_{\perp} \propto f^{3}$
- Long-range minimized by structure design
- Short range under control by ensuring a minimum aperture (~2.5 mm radius)and very good alignment (<10μm)

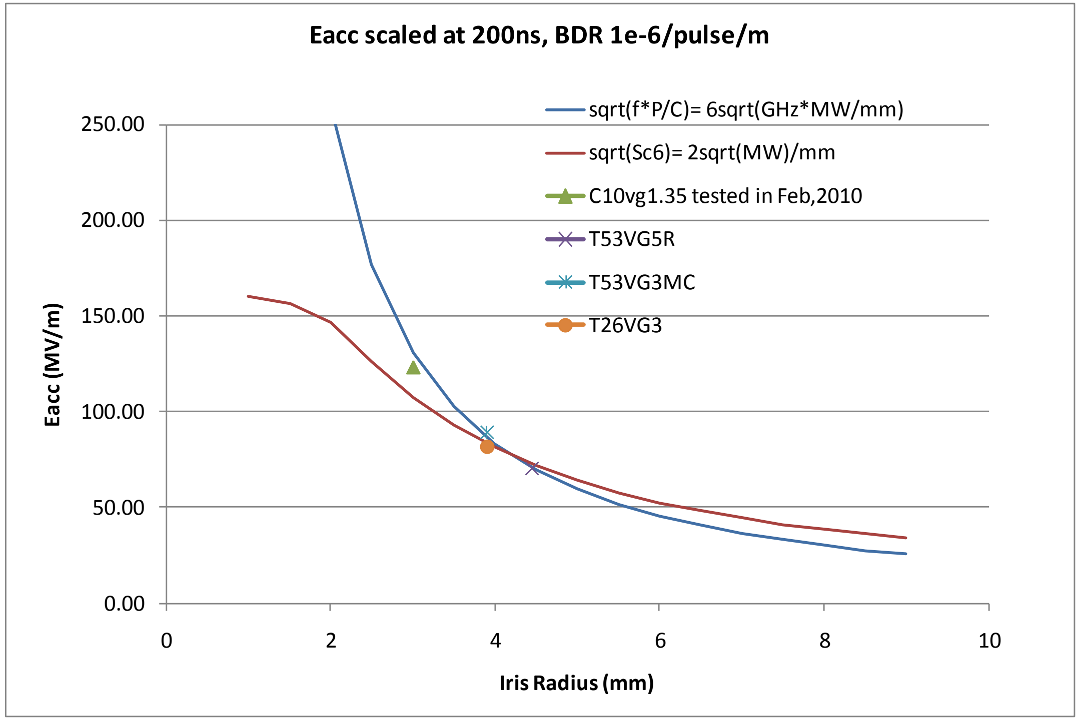
Accelerating structure specs II

Beam dynamics:

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

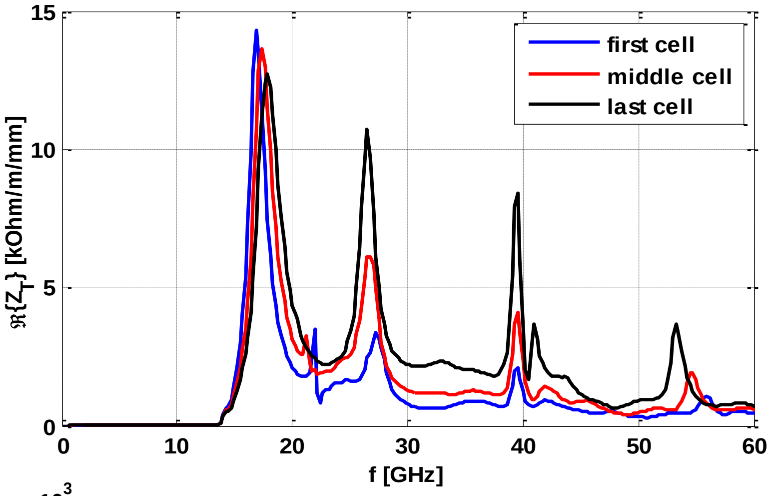
$$W_t \propto a^3$$

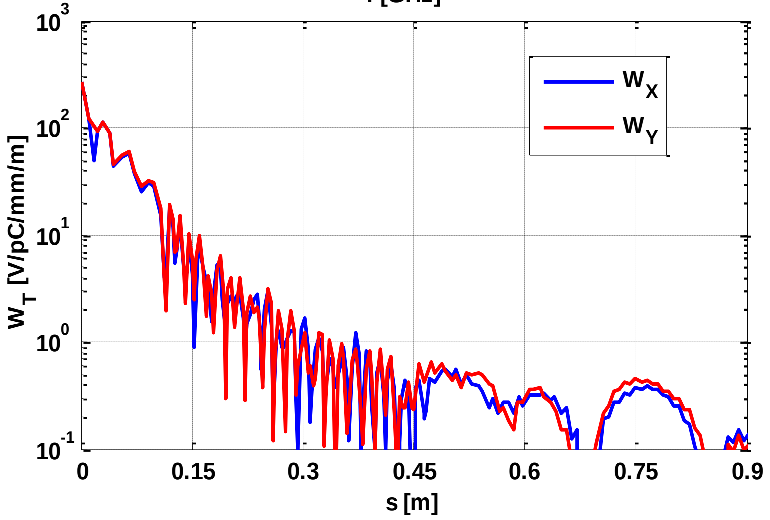
RF power flow and/or iris aperture apparently have a strong impact on achievable E_{acc} and on surface erosion.
Mechanism not fully understood but it means <u>we can not achieve high gradient without generating strong wakefields</u>



Waveguide damping I

Wake fields calculated by FEM codes in frequency and time domain





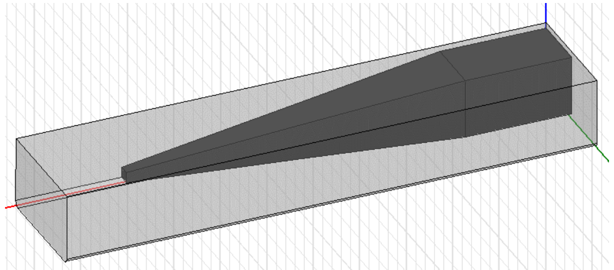
We add to the original cell four waveguides11 mm wide through which wakefields can propagate.
This gives a cutoff frequency of 13.6 GHz for the $TE_{1,0}$ which is given by the relation:

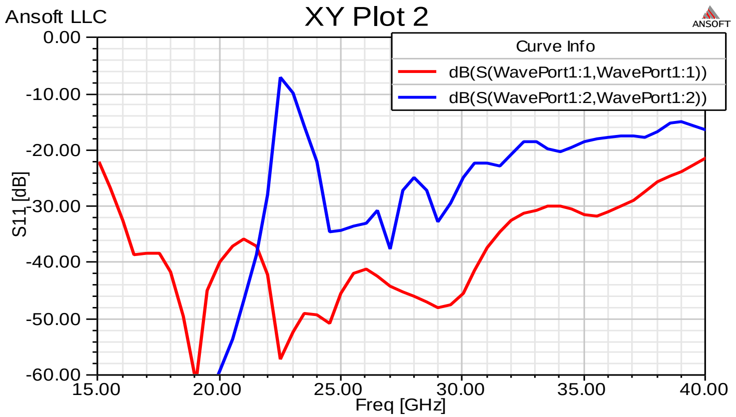
$$f_0 = \frac{c}{2a}$$

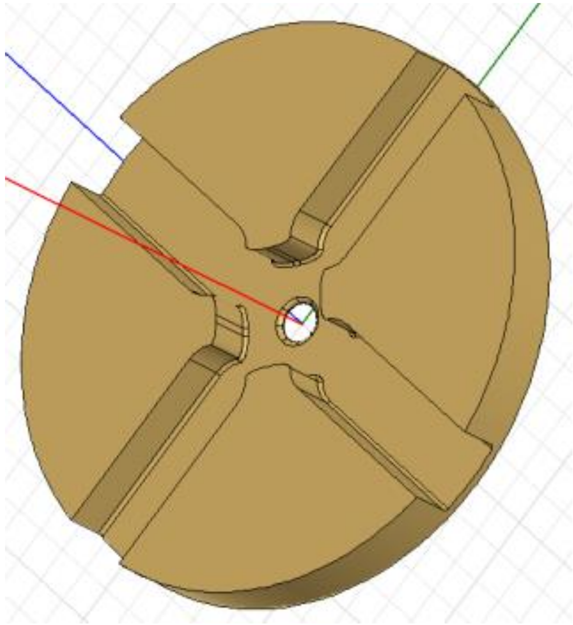
18 GHz propagates, 12 GHz does not!!

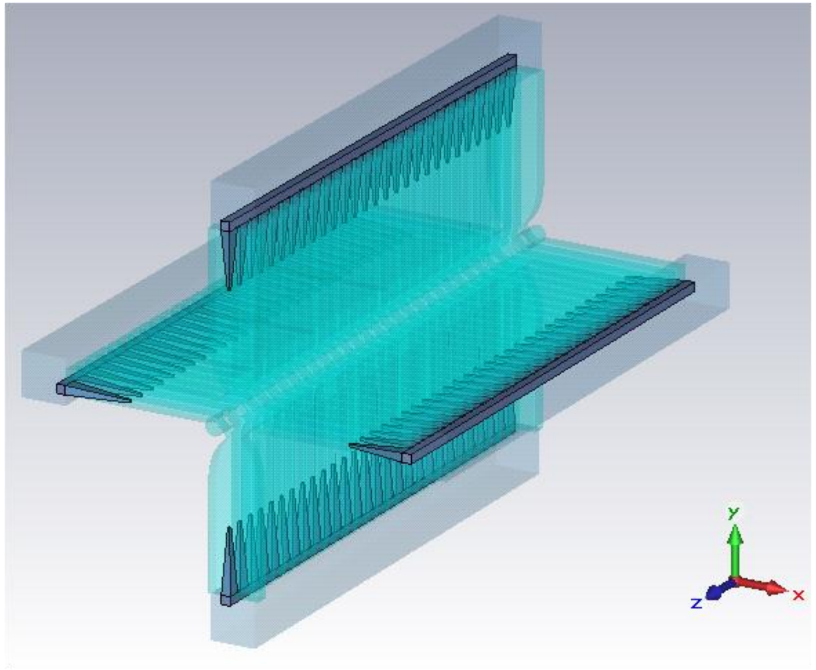
Cell	First	Middle	Last
Q-factor	11.1	8.7	7.1
Amplitude [V/pC/mm/m]	125	156	182
Frequency [GHz]	16.91	17.35	17.80

Waveguide damping II

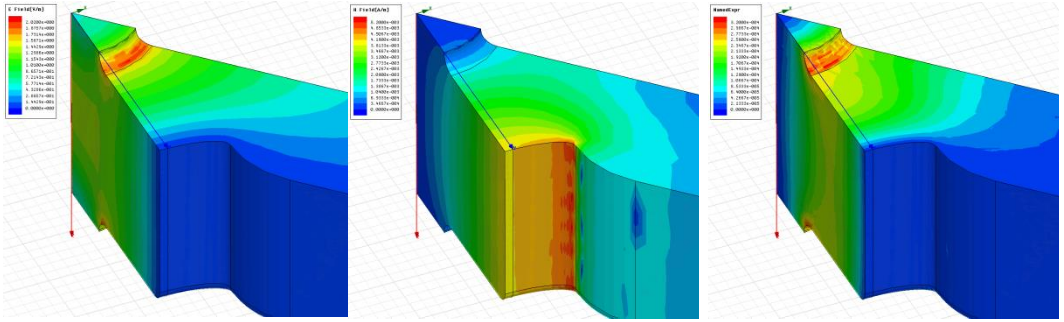






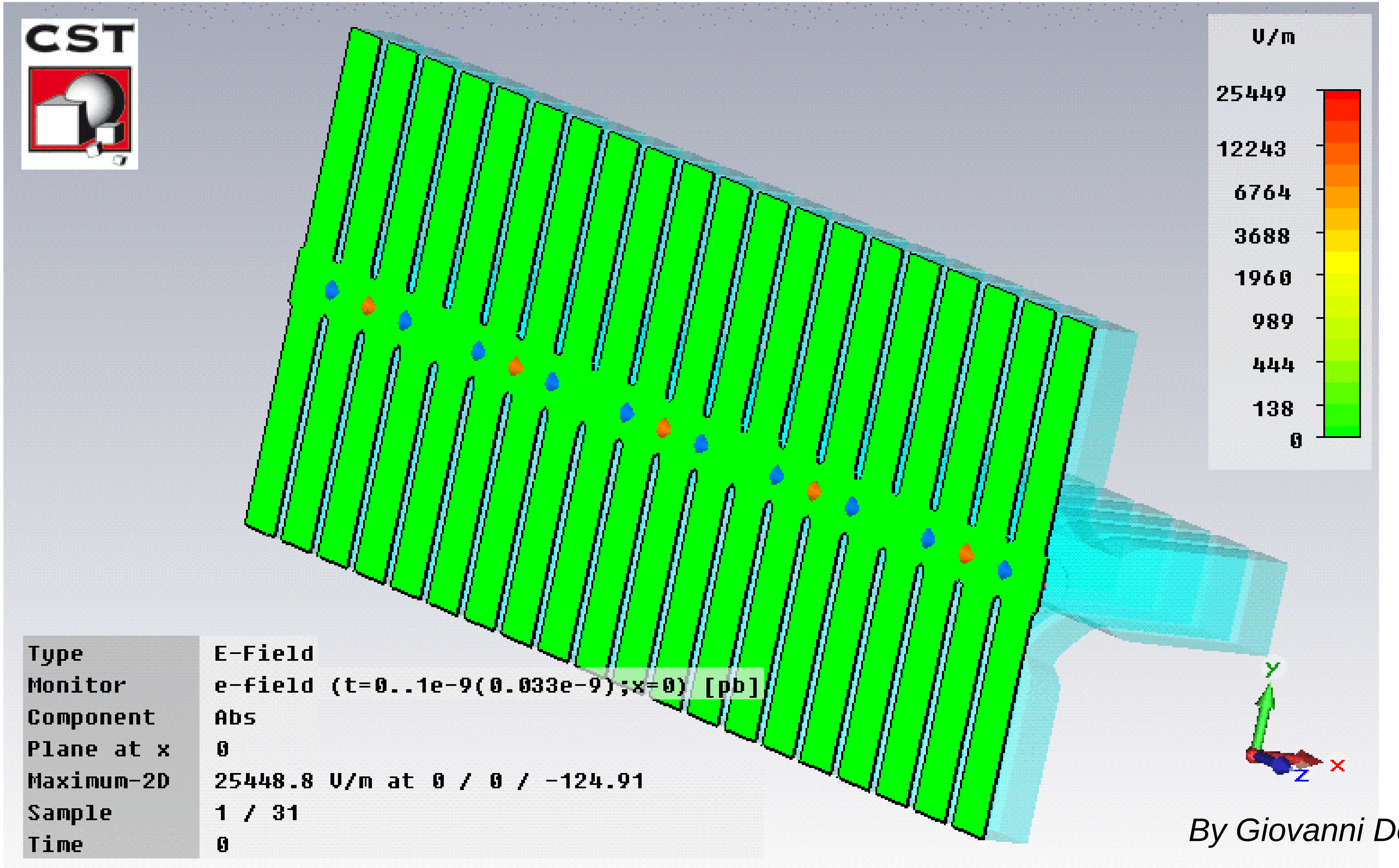


E_s/E_a H_s/E_a S_c/E_a^2



A SiC absorber at the end of the waveguide will absorb the energy of wakefields

Further optimization of the shape to minimize pulse heating, surface field, and the poynting vector

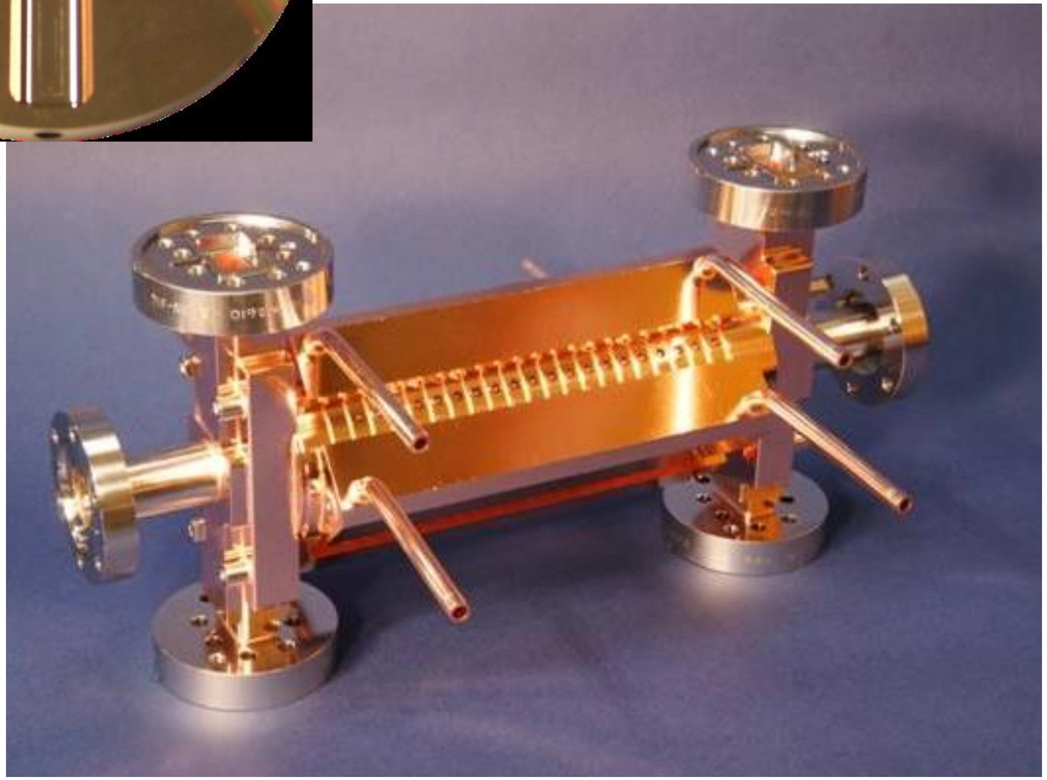


By Giovanni De Michele

The CLIC accelerating structure

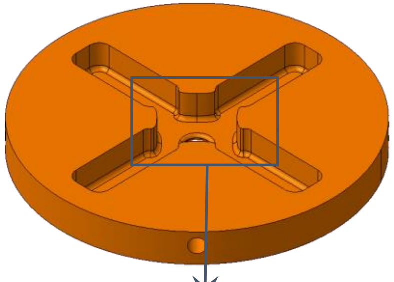
Table 5.29: Structure parameters

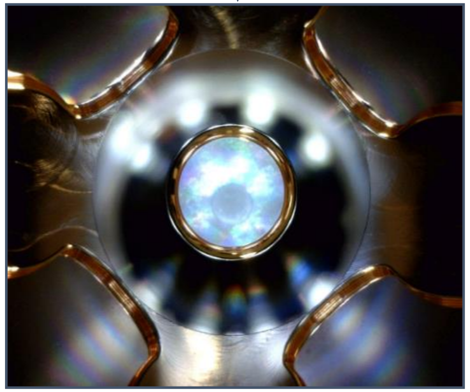
Average loaded accelerating gradient	100 MV/m
Frequency	12 GHz
RF phase advance per cell	$2\pi/3$ rad
Average iris radius to wavelength ratio	0.11
Input, output iris radii	3.15, 2.35 mm
Input, output iris thickness	1.67, 1.00 mm
Input, output group velocity	1.65, 0.83% of c
First and last cell Q-factor (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	244 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



Structure manufacturing

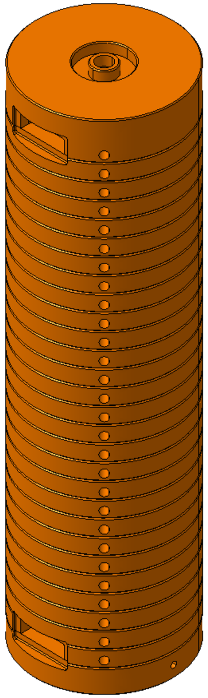
AS DISC





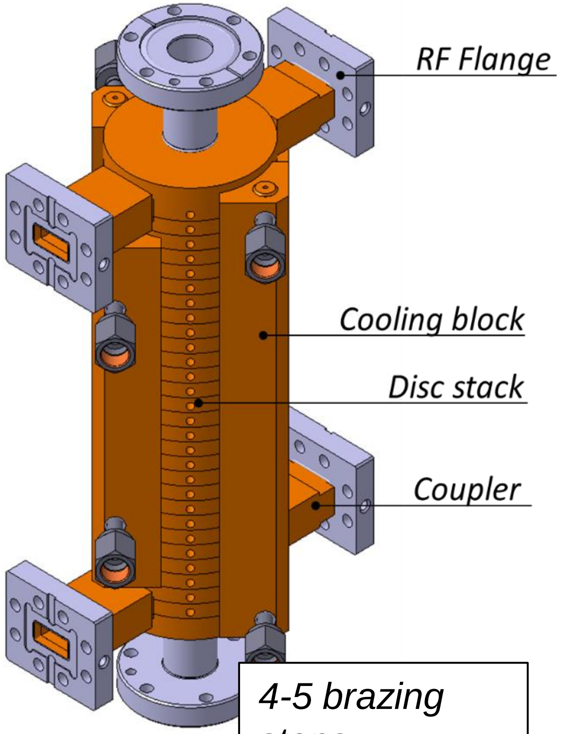
Acceptance at CERN

AS DISC STACK BONDING



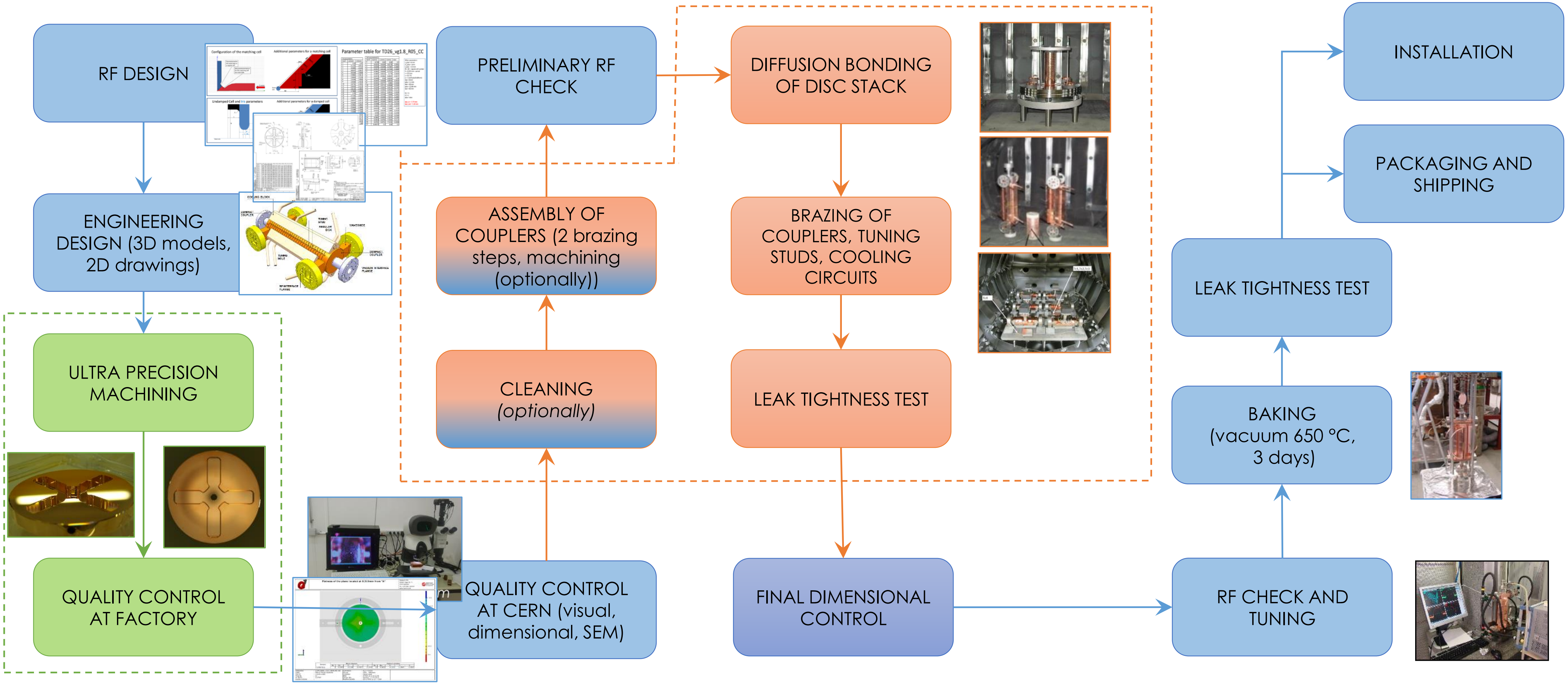
Acceptance at CERN

AS ASSEMBLY



4-5 brazing steps

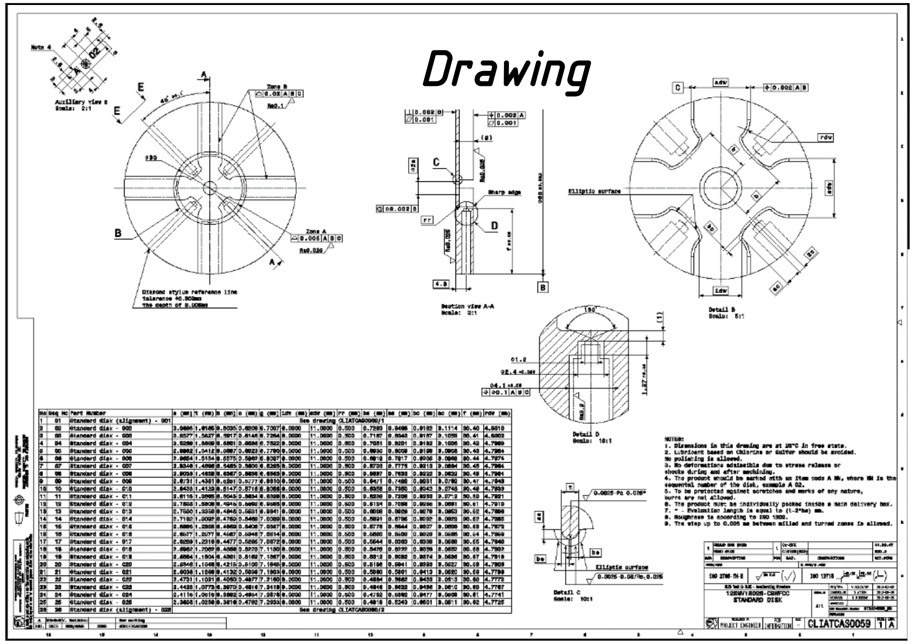
Baseline manufacturing flow



- CERN
- Companies for UP machining of components
- Companies for brazing/bonding

By Anastasiya Solodko

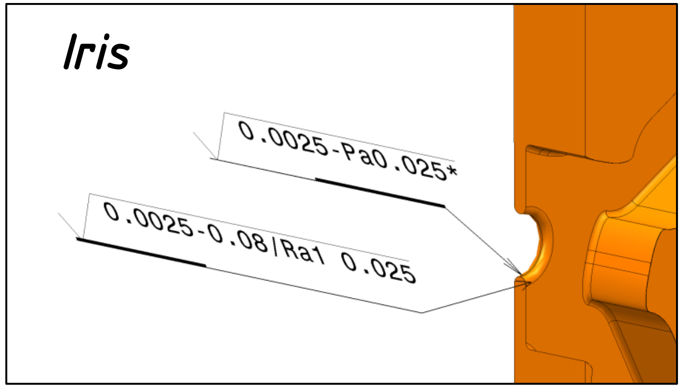
Machining. Tolerances

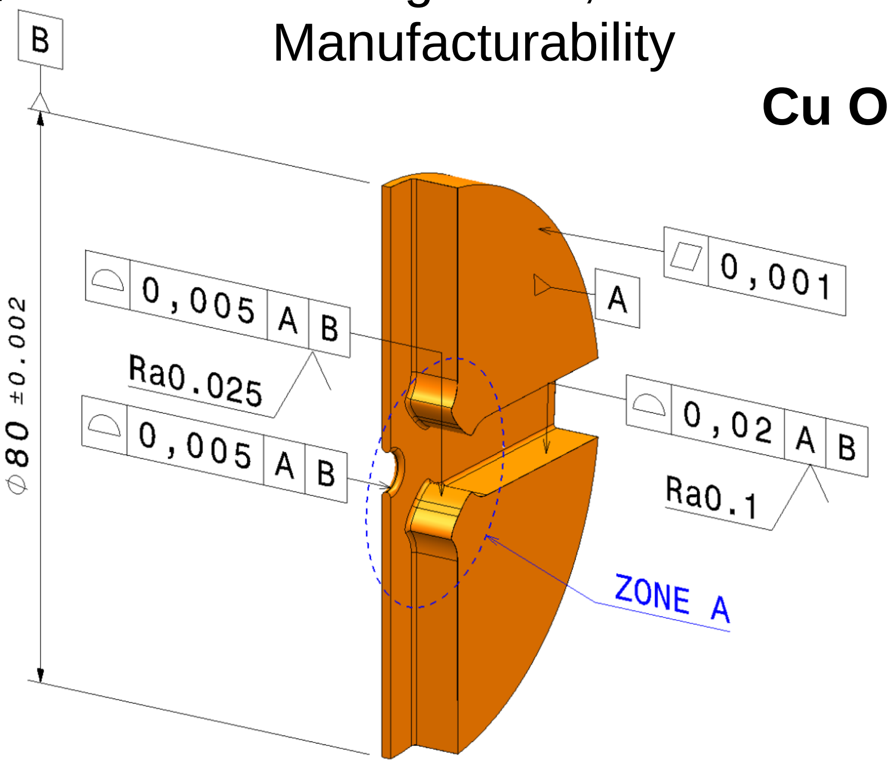


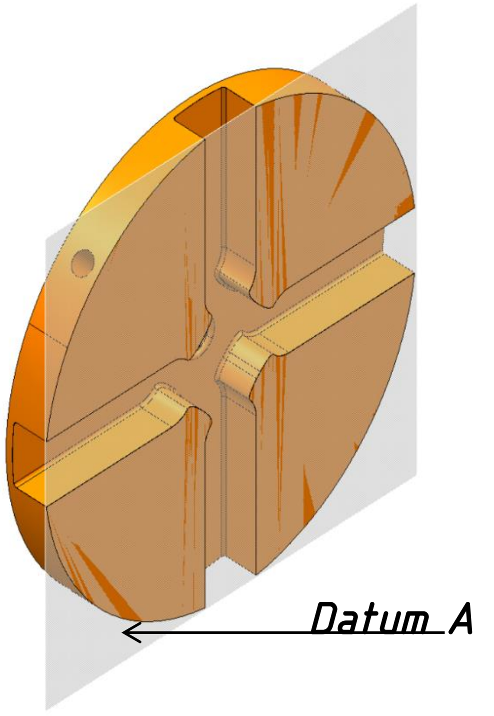
Tolerances required to satisfy the RF and beam dynamic constraints
Wakefields,
alignment,
Manufacturability

Cu OFE

Cell shape accuracy:
zone A – 0.005 mm
zone B – 0.02 mm
Flatness – 0.001 mm
Surface roughness:
zone A Ra 0.025 µm
zone B Ra 0.1 µm

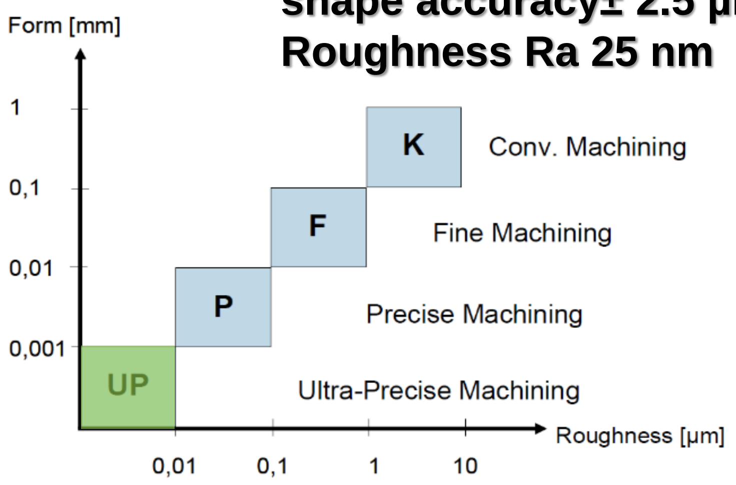






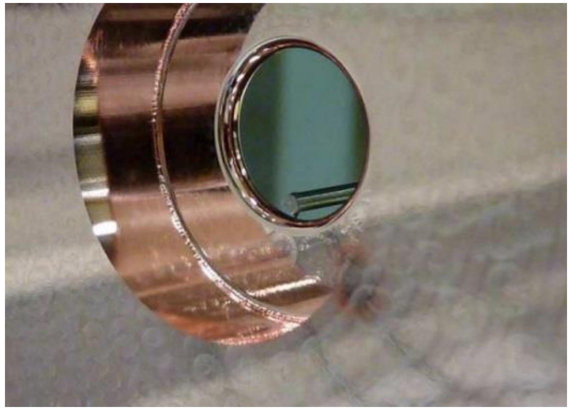
Machining. Technology

CLIC's needs:
shape accuracy± 2.5 µm
Roughness Ra 25 nm



S. Atieh

Single diamond turning and milling

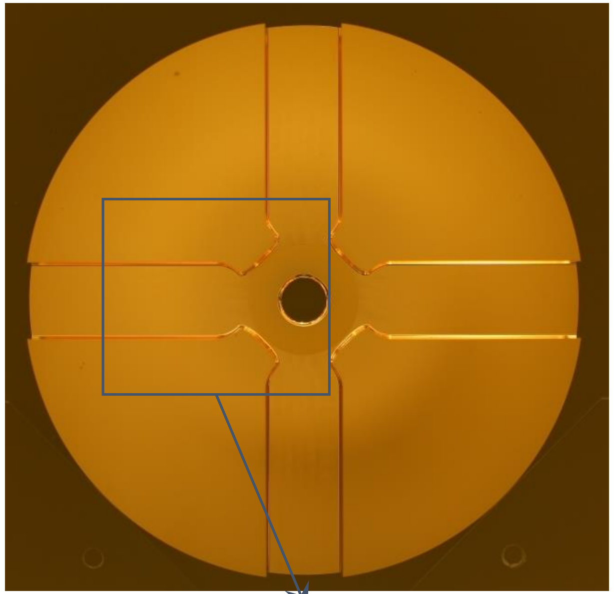


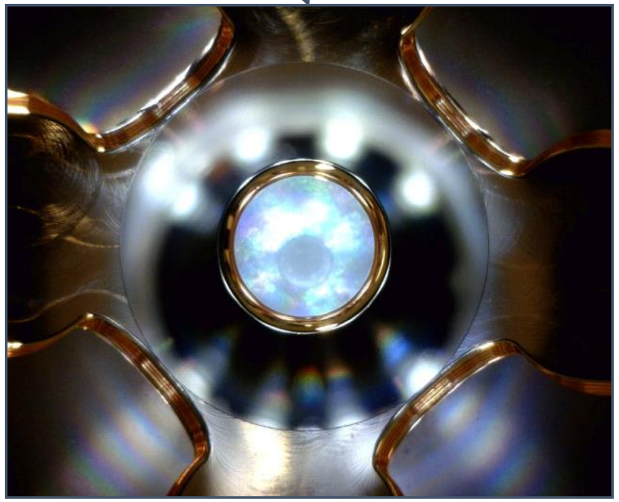
Pre machining

- Sawing
- Pre-Turning
- Pre-milling
- Drilling tuning holes
- (Measurement)
- (Annealing)

End machining

- UP turning side waveguides
- UP turning opposite side
- UP milling waveguides
- Iris final turning
- (Metrology)
- (Cleaning)





Quality assurance

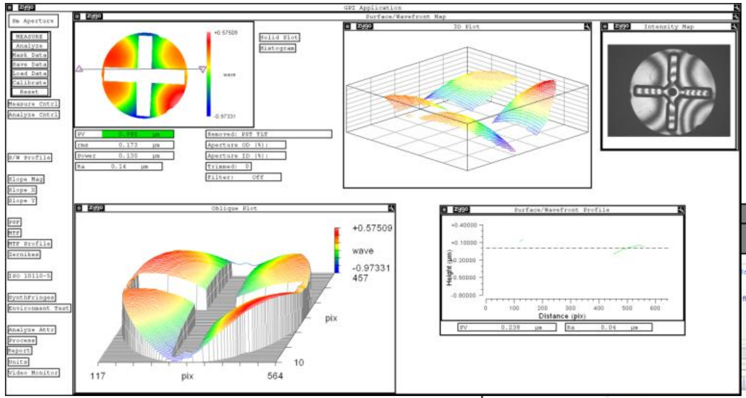
- Full metrology and microscopy in selected disks
- Simplified metrology of all disks at the manufacturer
- Non contact measurements for flatness control
- SEM looking for machining marks, pollution, burrs

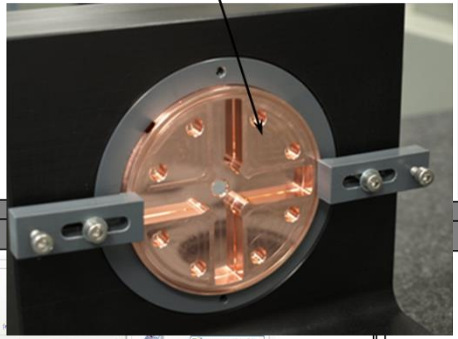
Enabling Technologies Group — Inspection Report

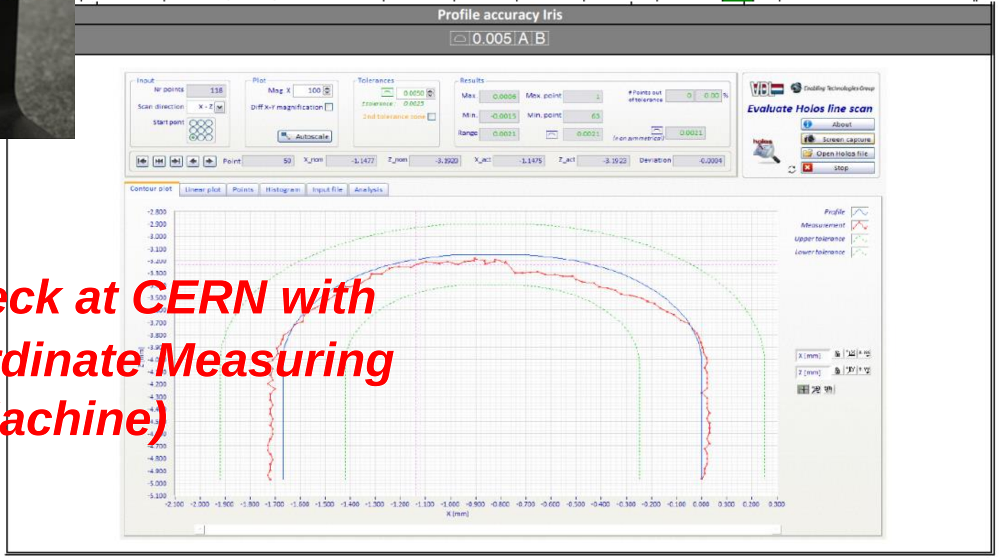
Drawing no.	CLIAAS120064	Prod. Nr.	2
Description	Disk 01		

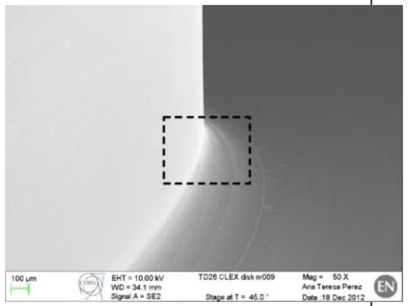
Dimensions

Measurand	Description	Nominal	Upper	Lower	Actual	Deviation	Pass √	Fail √	Remark
1	Ref A 0.002	0.0000	0.0020	0.0000	0.0013	0.0013	√		
2	Outer diameter Ref B	74.0000	0.0025	-0.0025	74.0002	0.0002	√		
3	0.002 ref B	0.0000	0.0020	0.0000	0.0009	0.0009	√		
4	0.002 A	0.0000	0.0020	0.0000	0.0002	0.0002	√		
5	Diameter 70	70.0000	0.0000	-0.0100	69.9953	-0.0047	√		
6	0.005 B	0.0000	0.0050	0.0000	0.0003	0.0003	√		
7	Diameter 2xa	6.3000	0.0050	-0.0050	6.2996	-0.0004	√		
8	Distance d	8.3098	0.0020	-0.0020	8.3105	0.0007	√		
9	Plane at distance d 0.002	0.0000	0.0020	0.0000	0.0014	0.0014	√		
10	Diameter 70	70.0000	0.0150	0.0100	70.0129	0.0129	√		
11	0.005 B	0.0000	0.0050	0.0000	0.0011	0.0011	√		
12	Distance t	1.6700	0.0025	-0.0025	1.6705	0.0005	√		
13	Distance g	6.6398	0.0025	-0.0025	6.6396	-0.0002	√		
14	Width cross Z+	11.2500	0.0025	-0.0025	11.2503	0.0003	√		
15	Symmetry cross Z +	0.0000	0.0025	-0.0025	-0.0003	-0.0003	√		
16	Width cross Z-	11.2500	0.0025	-0.0025	11.2510	0.0010	√		
17	Symmetry cross Z -	0.0000	0.0025	-0.0025	-0.0004	-0.0004	√		
18	Width cross Y-	11.2500	0.0025	-0.0025	11.2499	-0.0001	√		
19	Symmetry cross Y -	0.0000	0.0025	-0.0025	0.0007	0.0007	√		



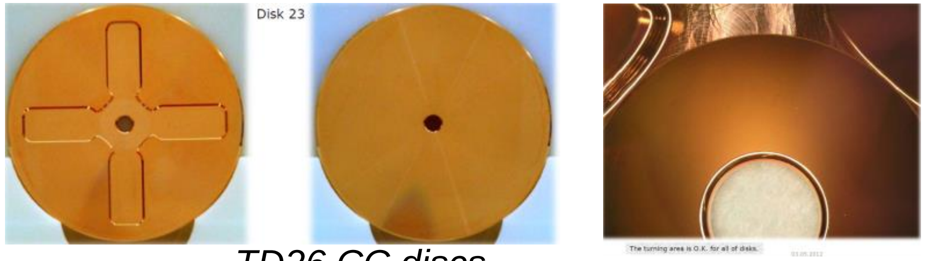






Double check at CERN with CMM (Coordinate Measuring Machine)

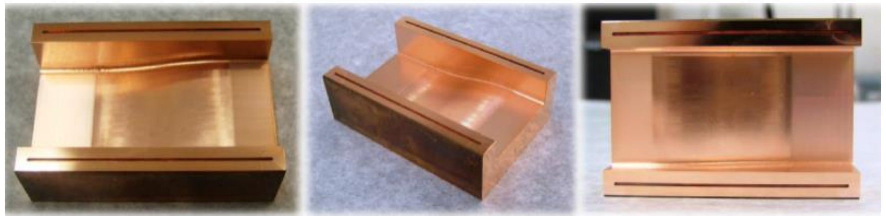
Acceptance and visual inspection.



TD26 CC discs

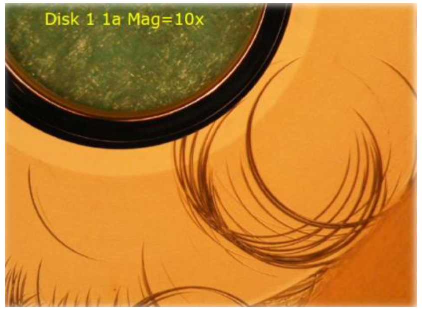
TD24 R05 couplers

TD24 R05 SiC manifolds



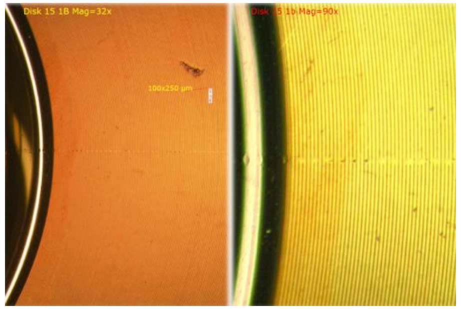
Machining deects

1. Milling marks in turning area



2. Scratches in RF area

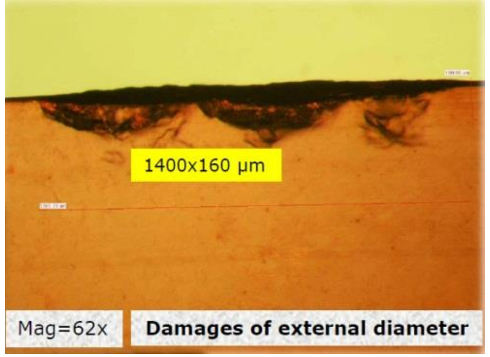
3. Visible indents/caverns in RF area



4. Burrs in sharp edges

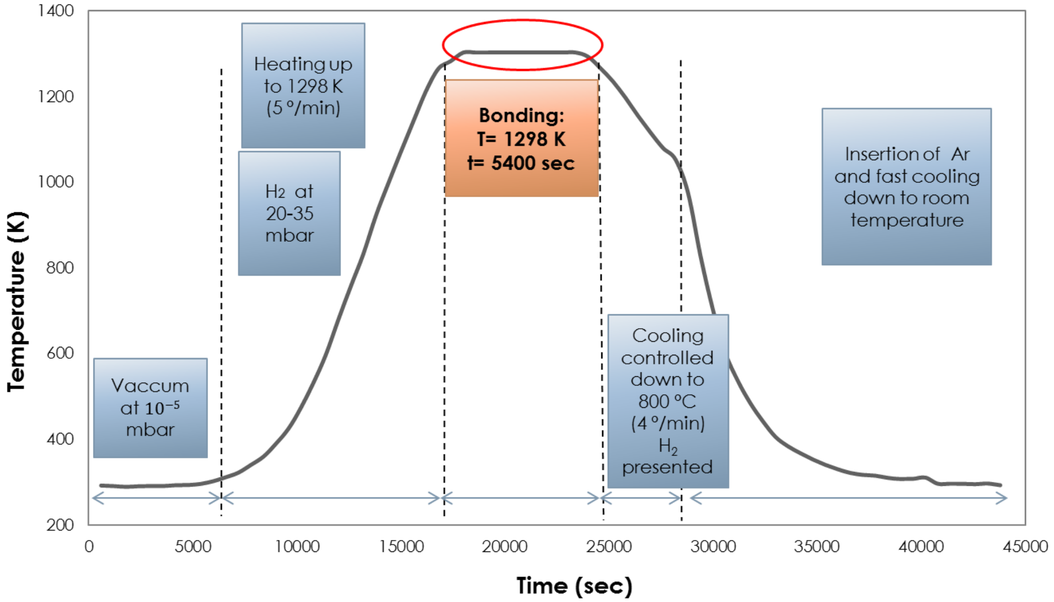
Andrey Olyunin
Nerea Mouriz Irazabal

5. Damages on external diameter

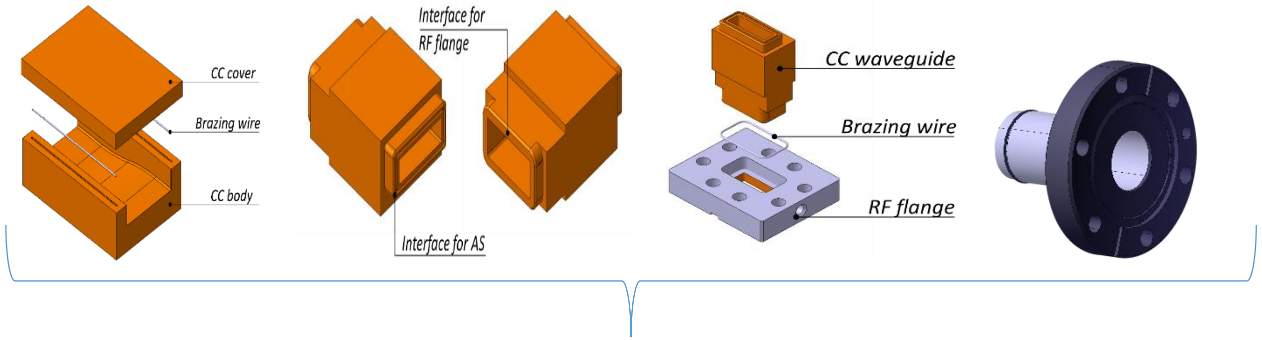


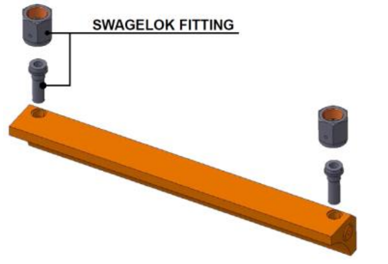
Diffusion bonding.

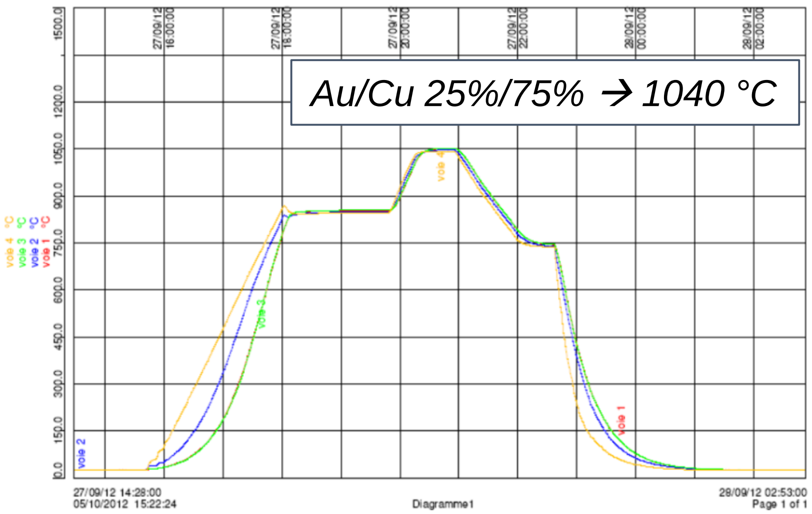
- Diffusion bonding to avoid additional material
- Alignment control before and after bonding
- Temperature ~1040 °C
- Vacuum 10^{-6} mbar
- H_2 partial pressure >20 mbar
- Applied pressure 0.1 MPa

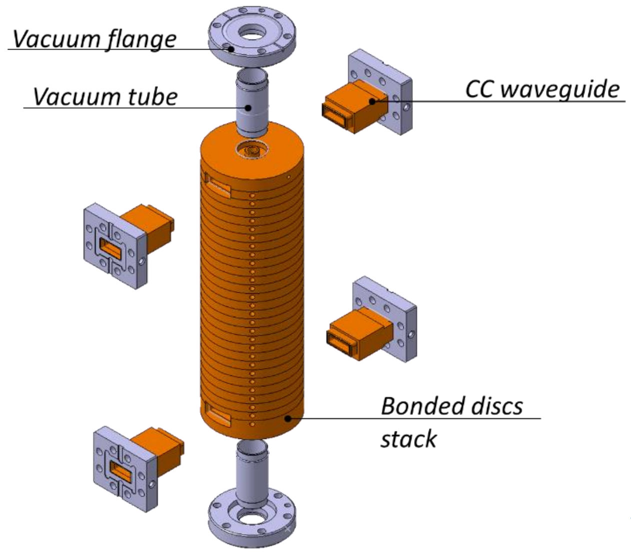


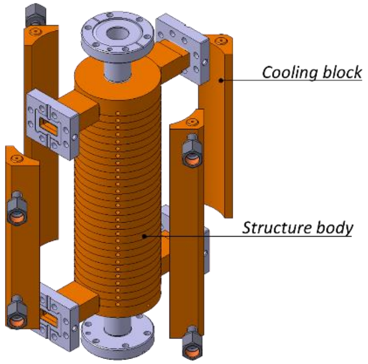
Brazing the rest of the structure





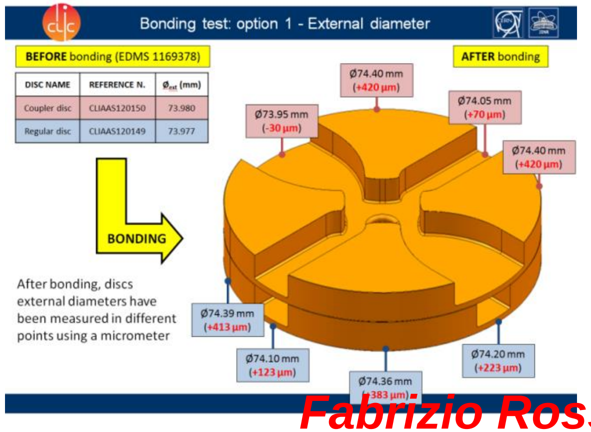






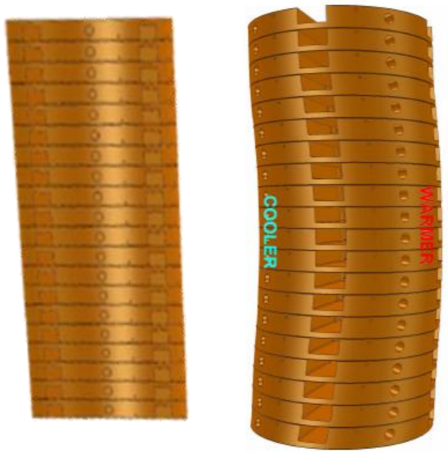
Bonding. Issues

Deformation (during the bonding process)

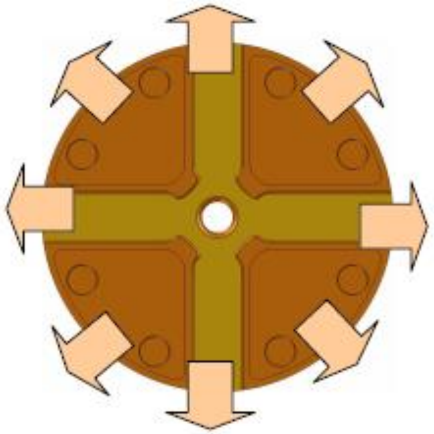


Fabrizio Rossi

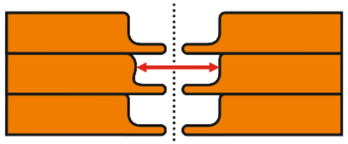
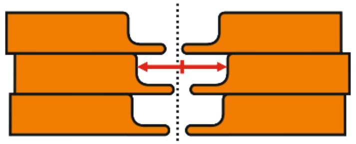
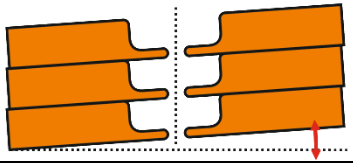
Asymmetrical heating or weight application



Extension → difficulties in assembling with another parts

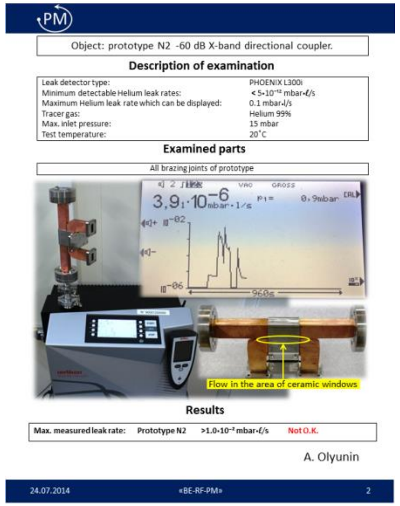


Misalignment (due to alignment and machining tolerances)

	Error in iris shape	Transversal offset	Tilt
Shape error			
Tolerance	1 µm [2,5]	5 µm [3]	140 µrad [2,5]

Brazing. Issues

Leak test



Object: prototype N2 -60 dB X-band directional coupler.

Description of examination

Leak detector type:	PHOENIX L300i
Minimum detectable Helium leak rates:	< $5 \cdot 10^{-12}$ mbar·ℓ/s
Maximum Helium leak rate which can be displayed:	0.1 mbar·l/s
Tracer gas:	Helium 99%
Max. inlet pressure:	15 mbar
Test temperature:	20°C

Examined parts

All brazing joints of prototype

Results

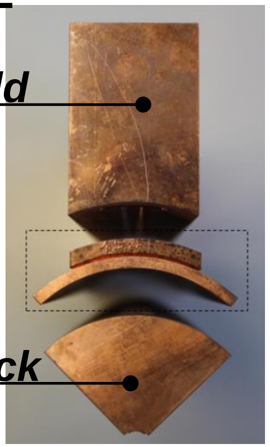
Max. measured leak rate:	Prototype N2	>$1.0 \cdot 10^{-2}$ mbar·ℓ/s	Not O.K.

A. Olyunin

24.07.2014 «BE-RF-PM» 2

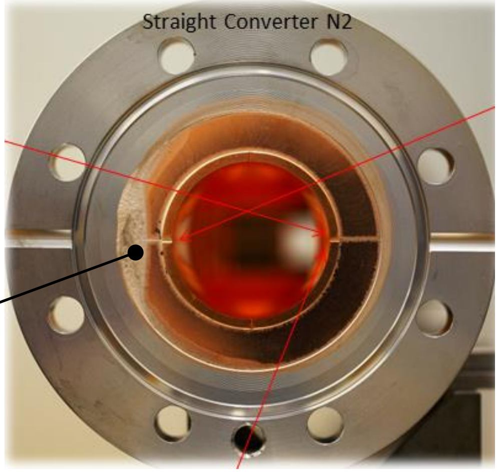
Brazing joint not tight

US test

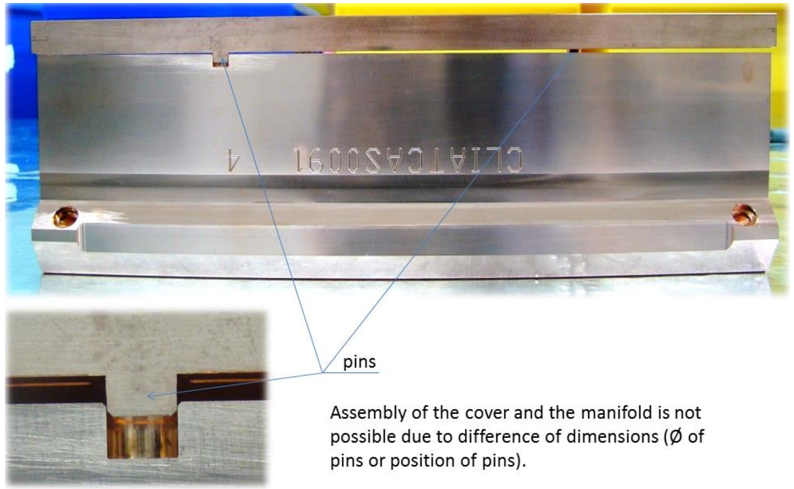


Brazing material leak

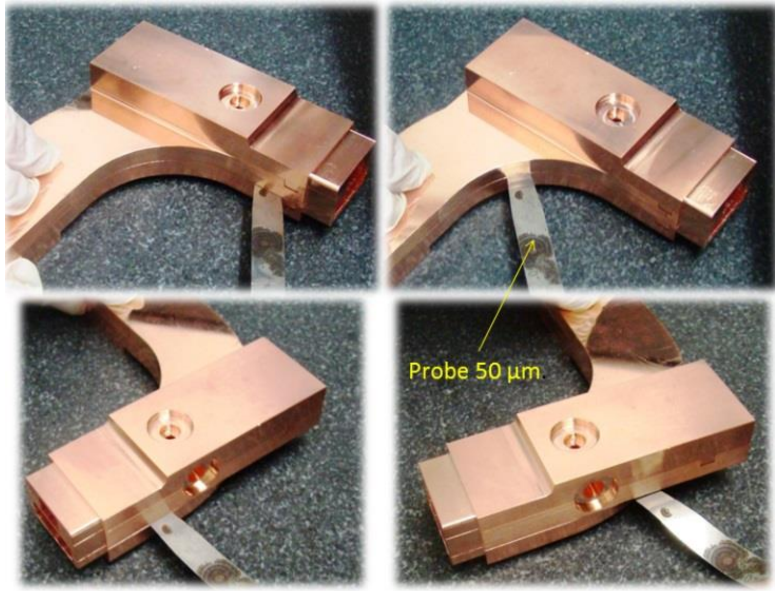
- Appears mainly with Ag/Cu brazing alloy.



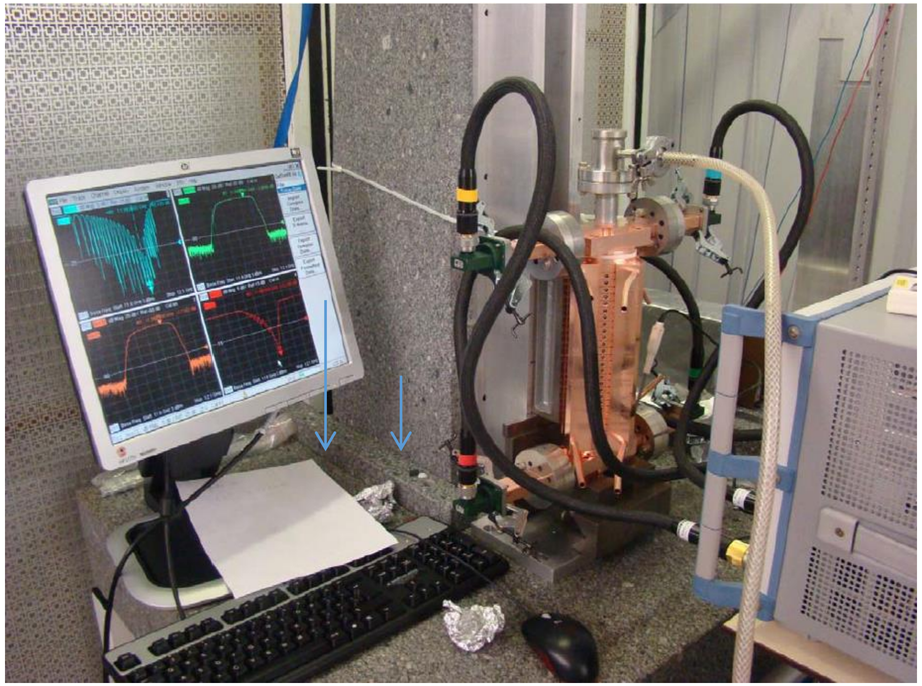
Dimension and tolerance issues

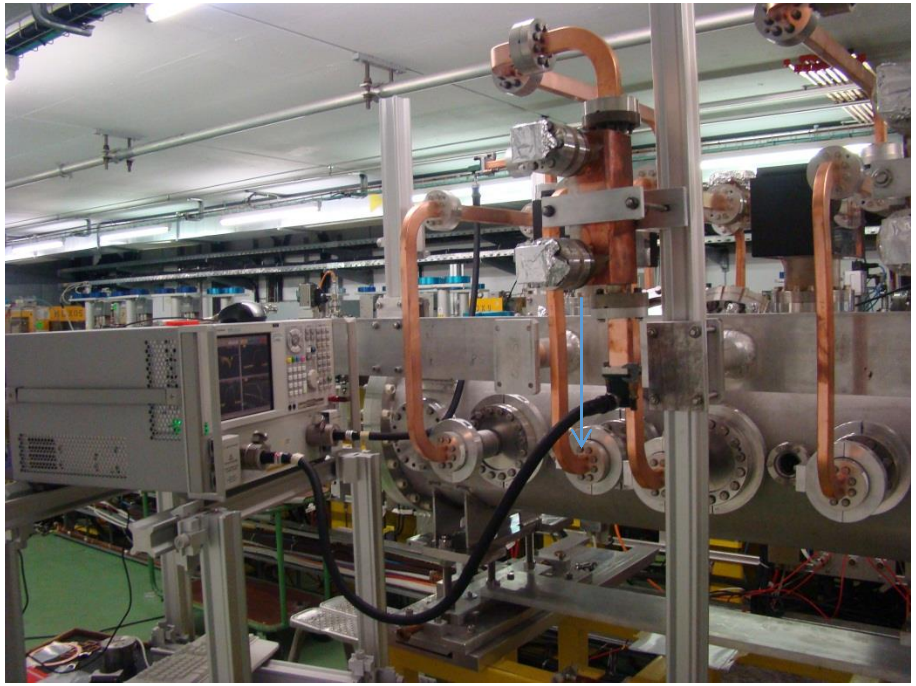


Assembly of the cover and the manifold is not possible due to difference of dimensions (Ø of pins or position of pins).



RF measurements and tuning





Transmission and reflexion

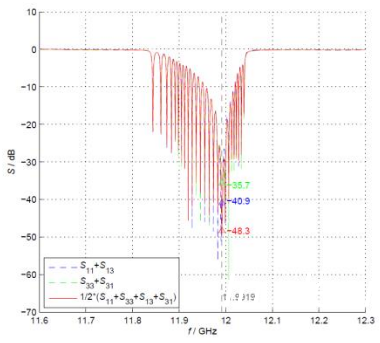
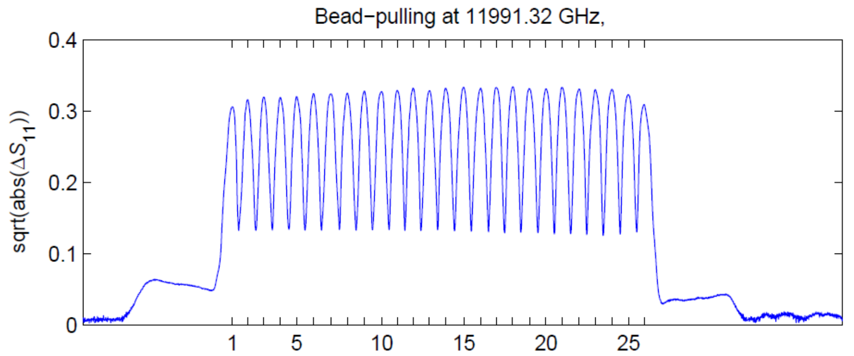


Figure 2: Reflection at input

Field homogeneity



Phase advance

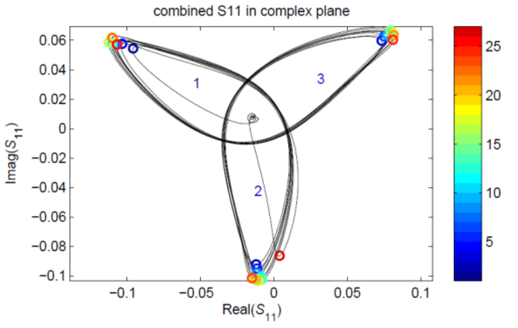
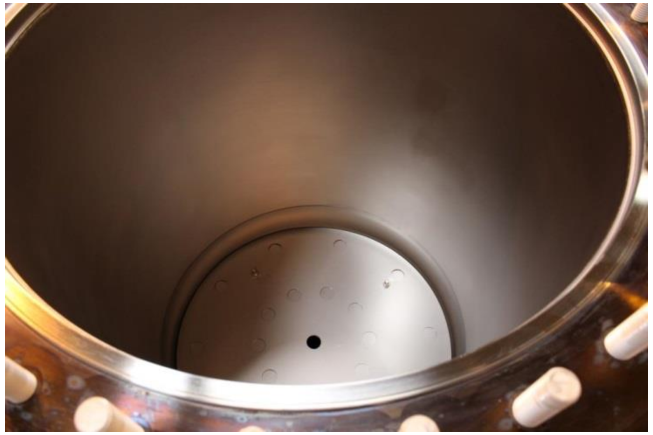
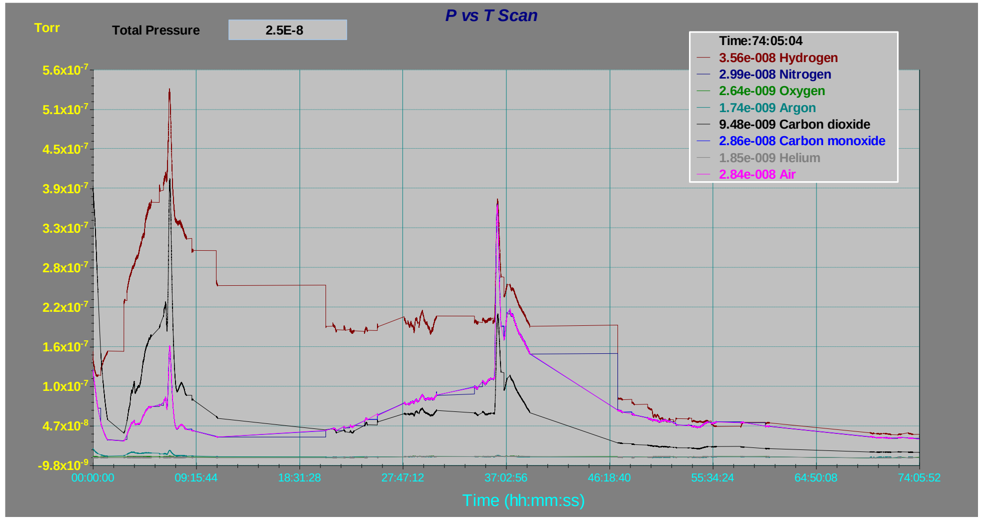


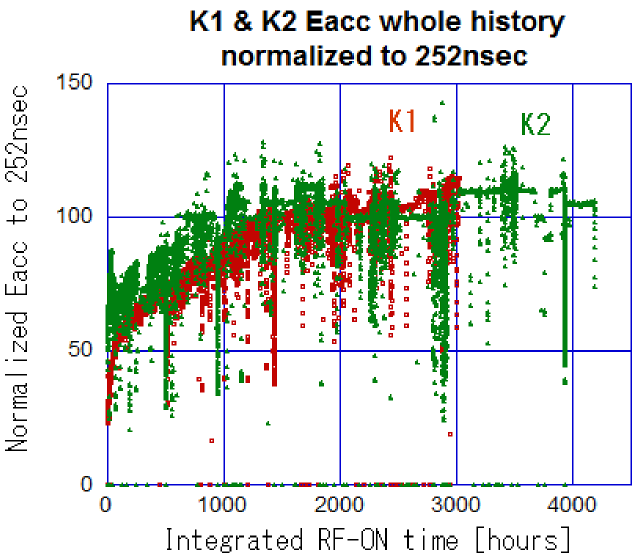
Figure 10: Bead-pulling at 11991.32 GHz

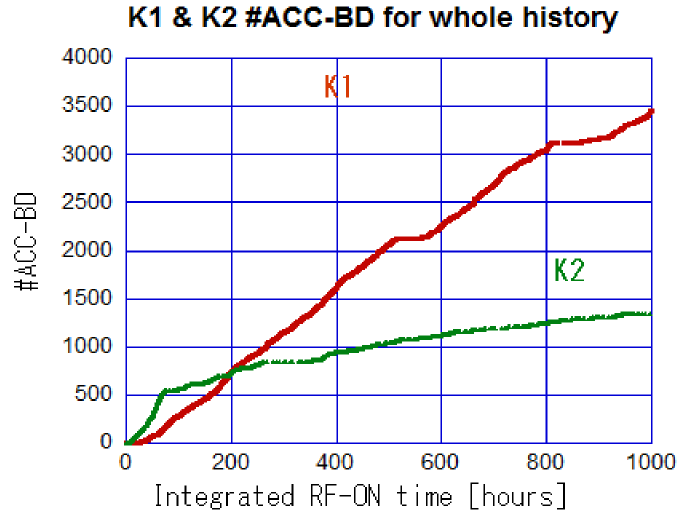
Vacuum baking

- Eliminates the H_2 diffused in the Cu surface during bonding
- Follows recipe from SLAC on NLC and KEK on JLC following breakdown studies
- T ~650 C for 1-2 days. Vacuum 10-9 mbar
- Under investigation in new prototypes

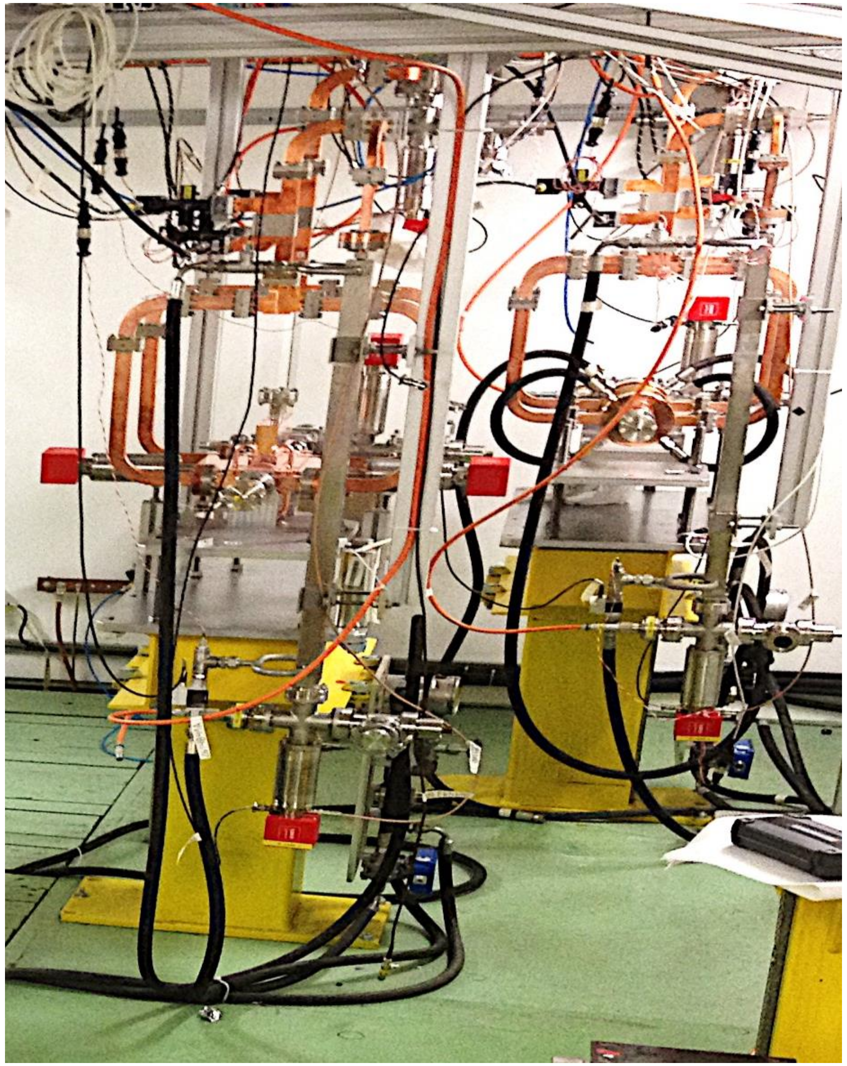


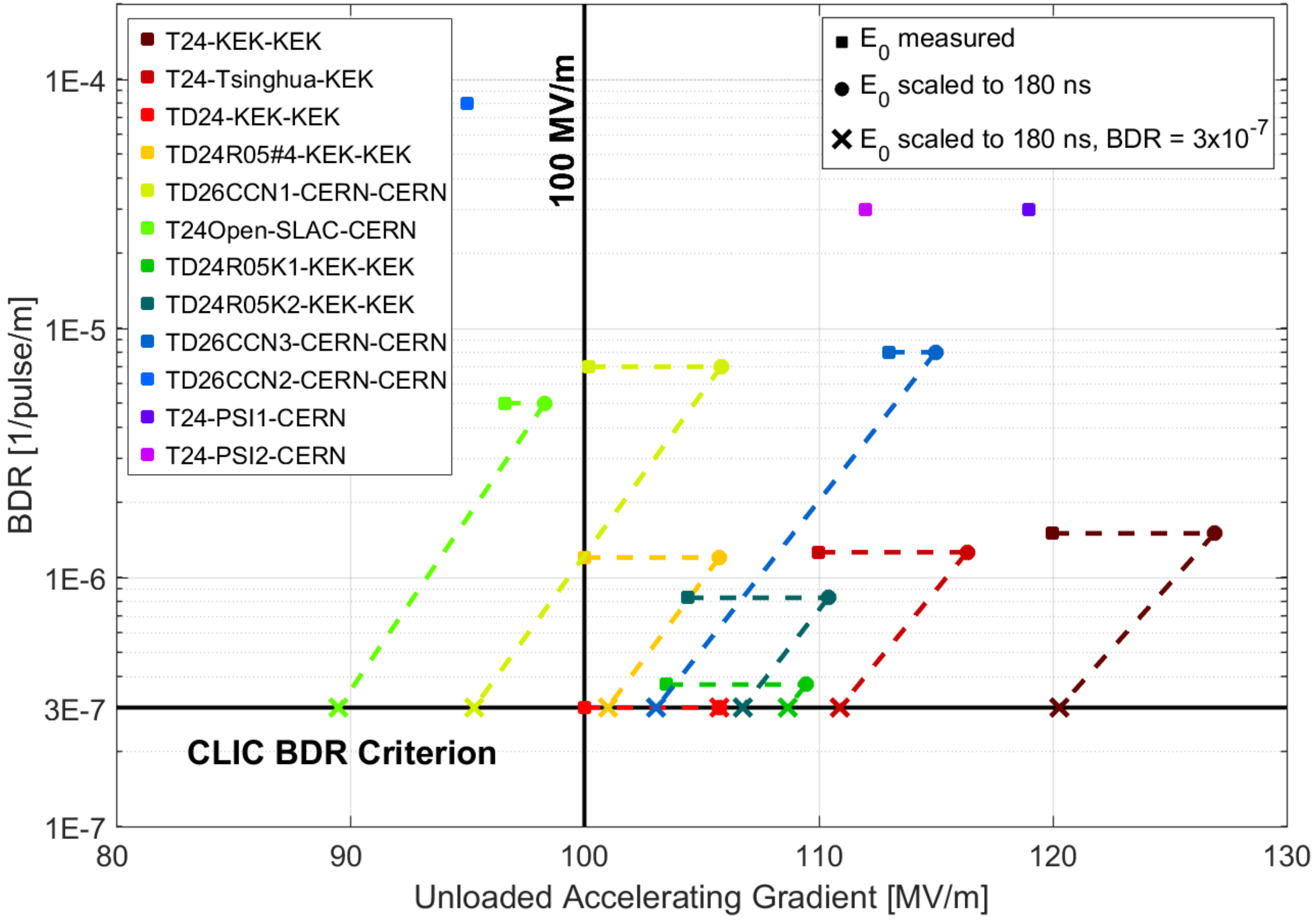




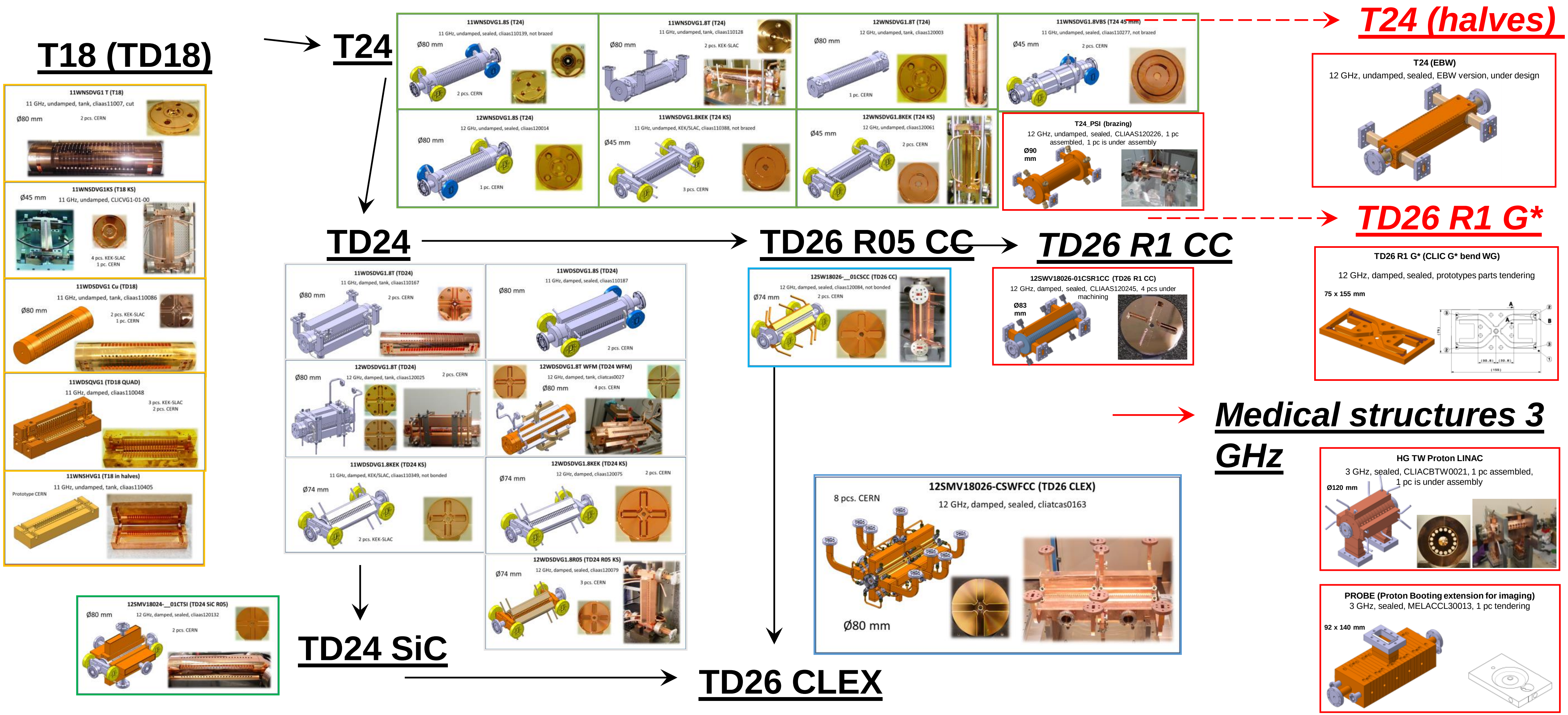


High power tests at CERN in xboxes

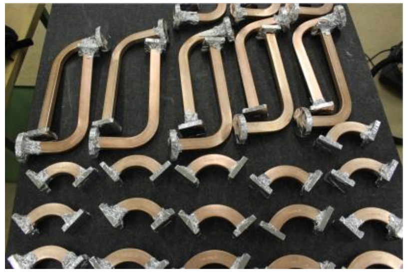


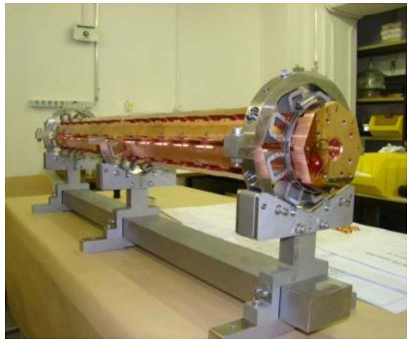


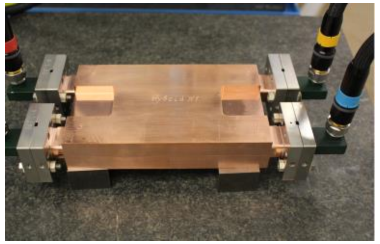
CLIC prototypes

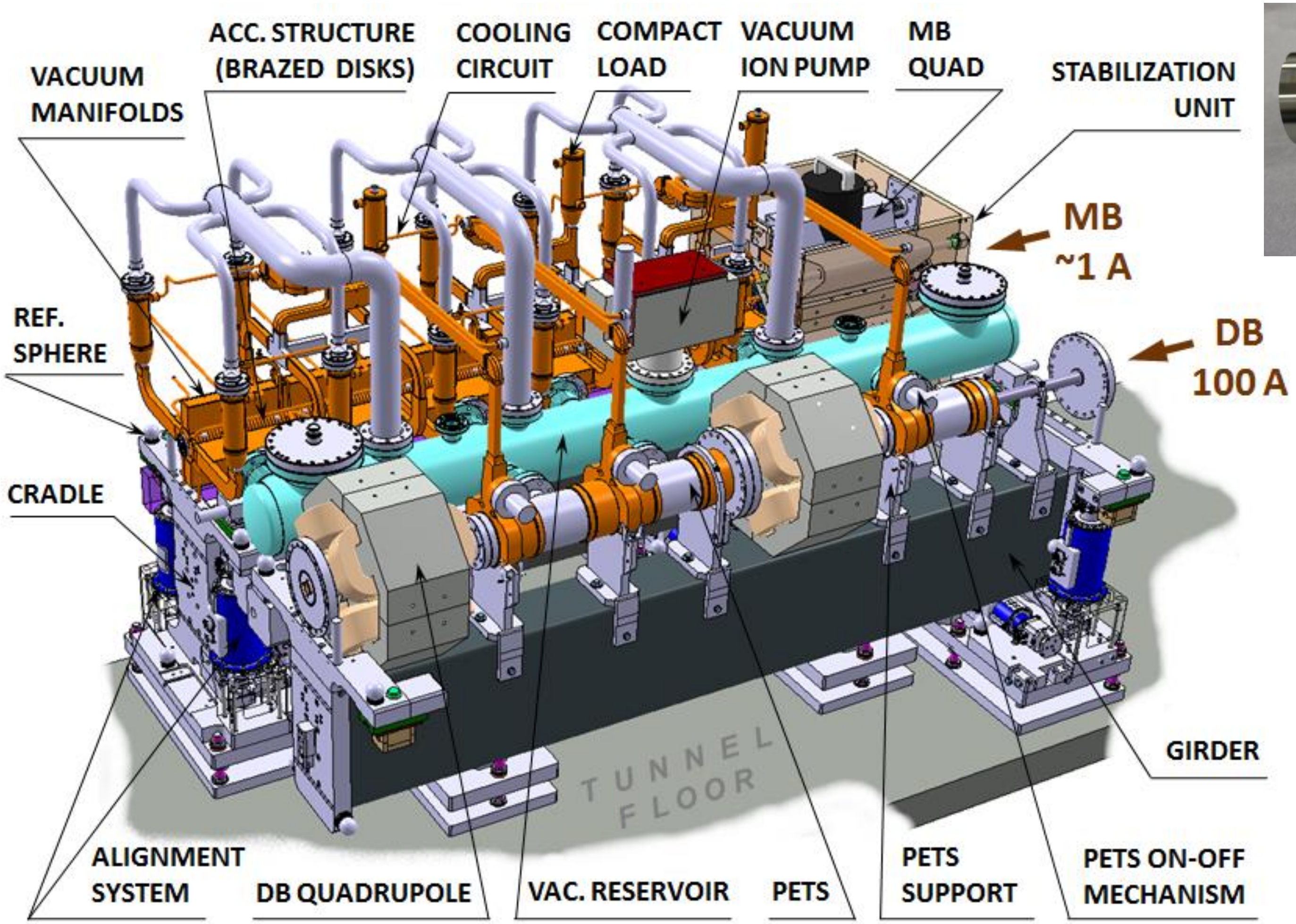


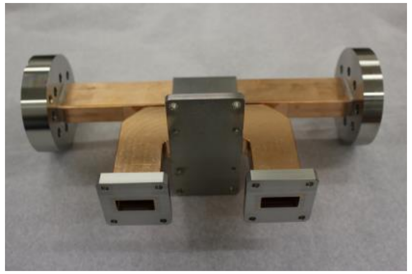
CLIC module. Other RF components



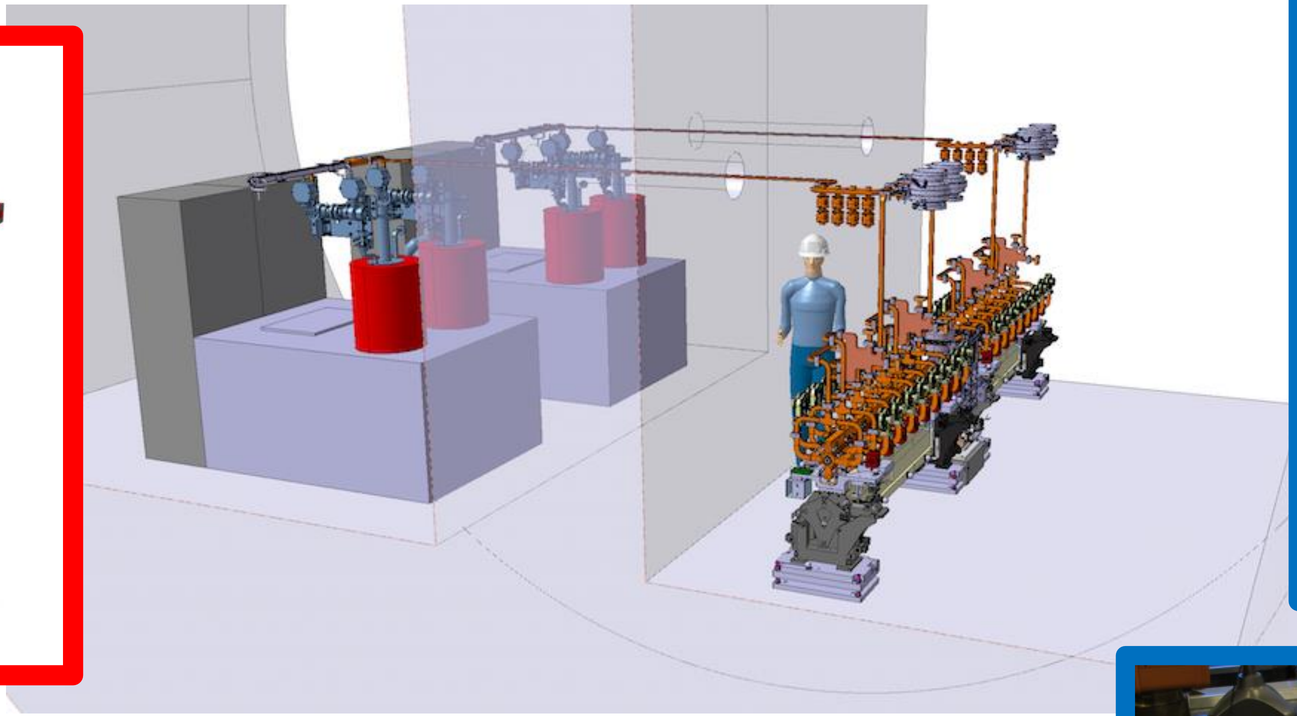


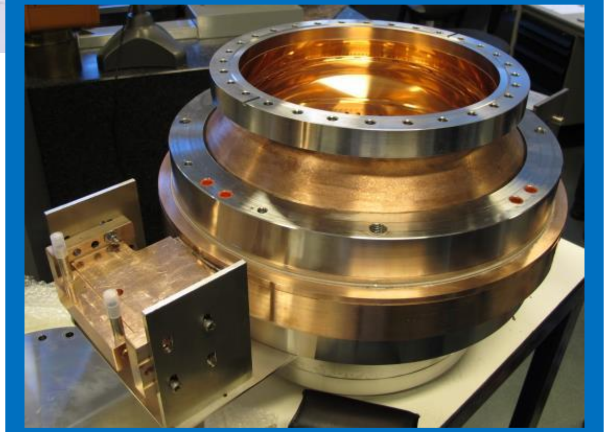






Power generation using klystrons





Modulators produce high voltage (~100's of KV) in a short pulse (~μs) which is sent to the **klystron** a sort of RF amplifier that converts kW coming from a generator onto MW of RF power at the appropriate frequency
A **pulse compressor** absorbs the RF, delays it and spits it back into a shorter but more powerful RF pulse!

CLIC instrumentation

CLIC Conceptual Design Report

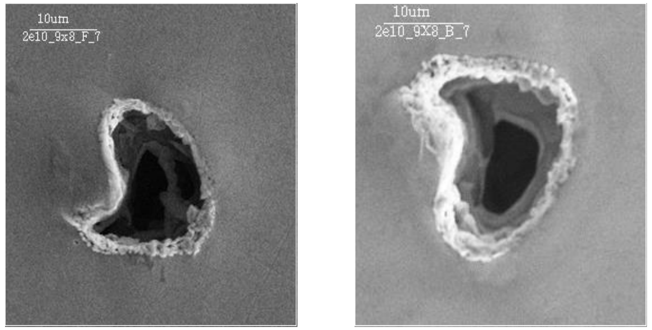
Development and Test of High Resolution Cavity BPMs for the CLIC Main Beam Linac

Main Instrumentation challenges for CLIC

- Measuring small emittance and small beam size
  - ~ 1μm spatial resolution Transverse Profile Monitors
- Non-invasive technique required to avoid damages
  - Laser wire scanner
  - Optical Diffraction radiation

Broken wire scanner

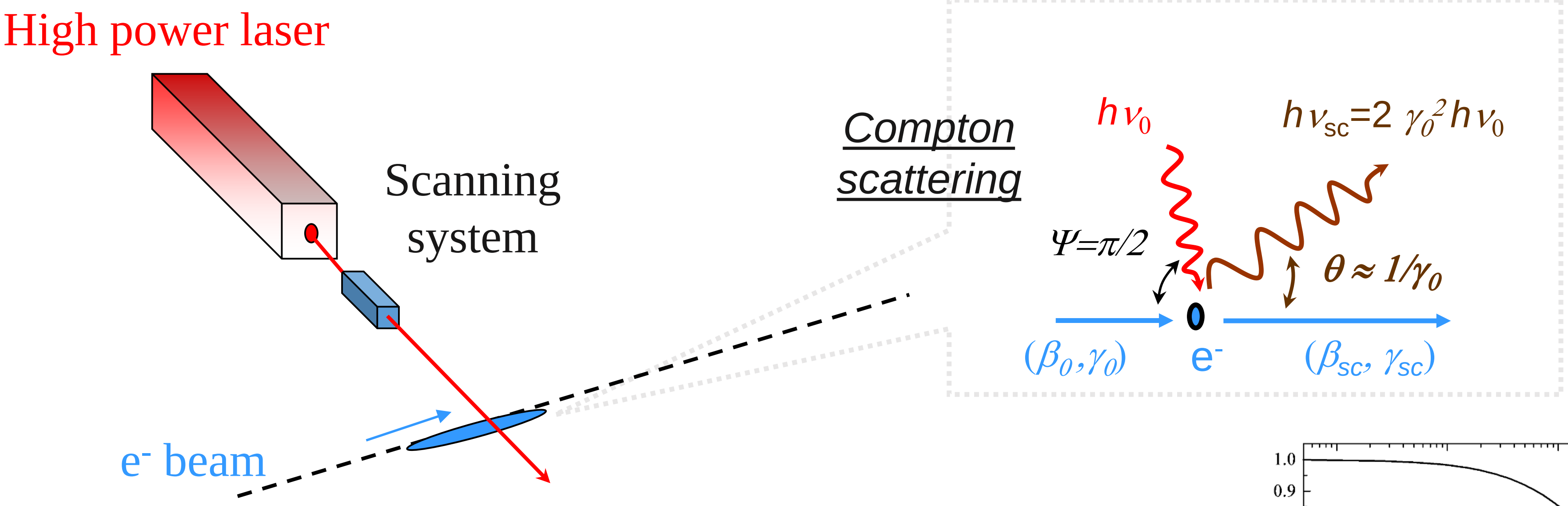
Broken screen

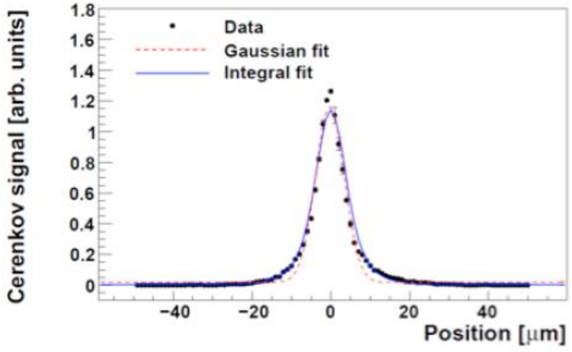


- Conservation of emittance over long distances relies on precise alignment
  - High accuracy (5μm)High resolution (50nm) cavity Beam Position Monitor – performance already demonstrated at ATF2/KEK
  - Wakefield monitor in CLIC accelerating structures (studied at CERN)

Beam size monitoring using Laser Wire scanner

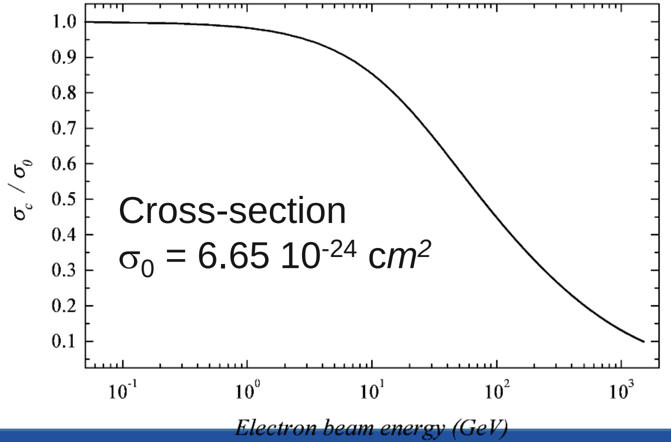
- Focusing a high power laser (waist ≈ 2λ) to scan through the beam
- Detecting scattered photons/electrons as a function of laser position using Cherenkov detectors, scintillators, etc.





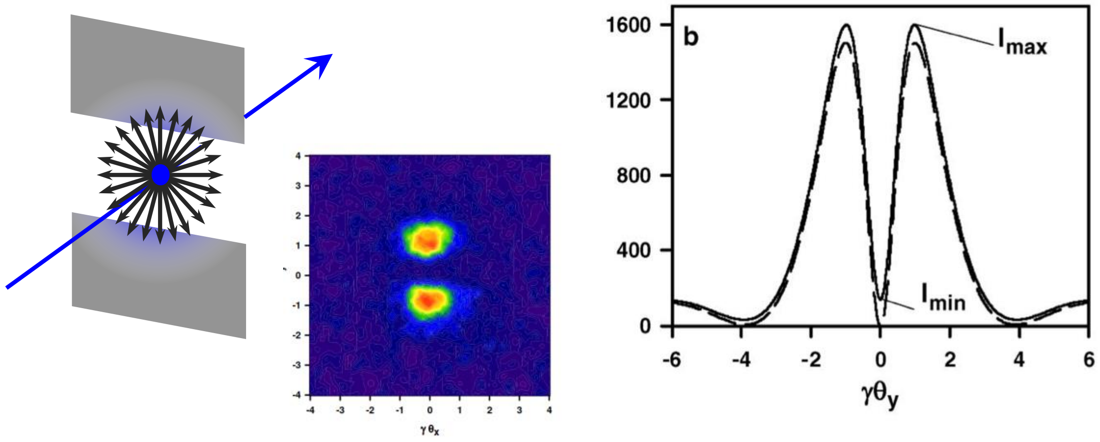
$$N_{interaction} \approx \frac{\sigma \cdot N_e \cdot N_{laser}}{A}$$

with A the interaction area, N_e and N_{laser} are the number of electrons and photons in A



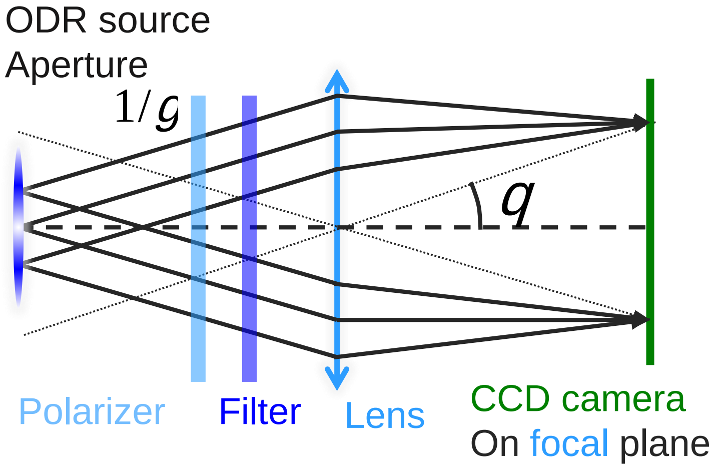
Beam size monitoring using Diffraction Radiation

- A cheaper and simpler alternative to Laser Wire Scanners
- An horizontal slit (aperture ≈ 10 σ) is used to measure a vertical beam size.
- The beam size is extracted from the visibility I_{min}/I_{max} of the projected vertical component of the ODR angular distribution



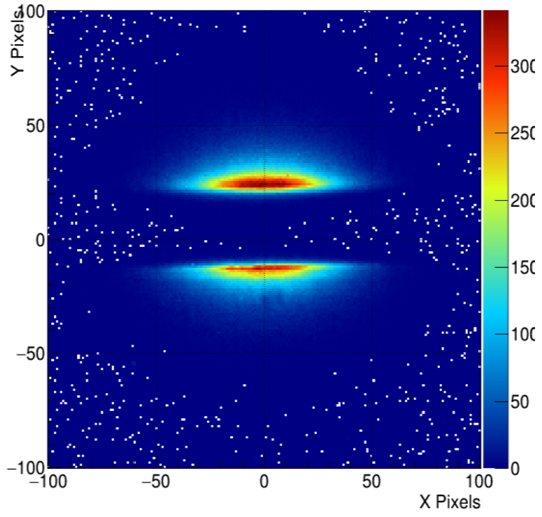
A polarizer is used to select only the **vertically polarized Optical Diffraction Radiation photons** and bandwith **filters** to choose the **wavelength**

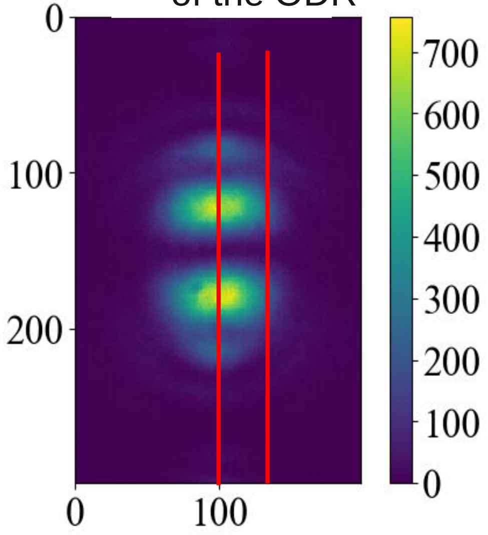
The **angular distribution** is obtained by putting the camera at the back focal plane of a **lens**

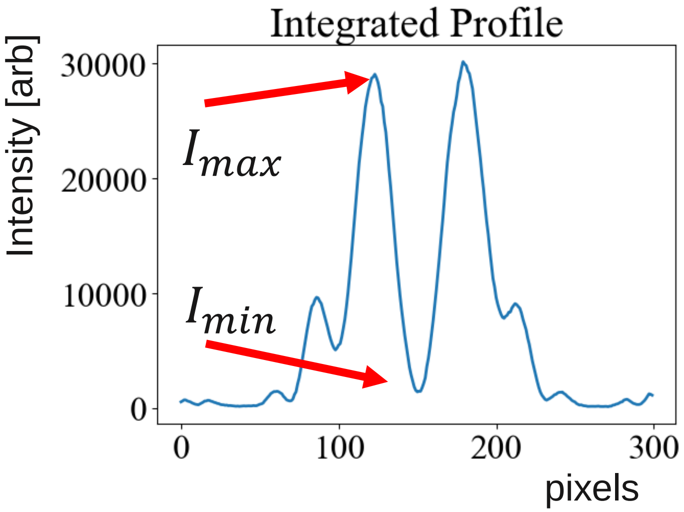


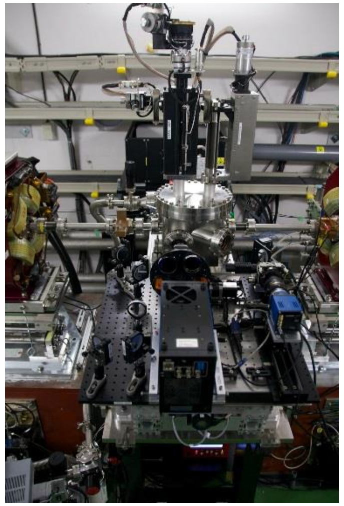
Beam size monitoring using Diffraction Radiation

- Prototype developed at ATF2@KEK





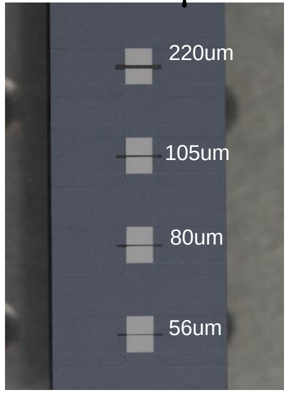


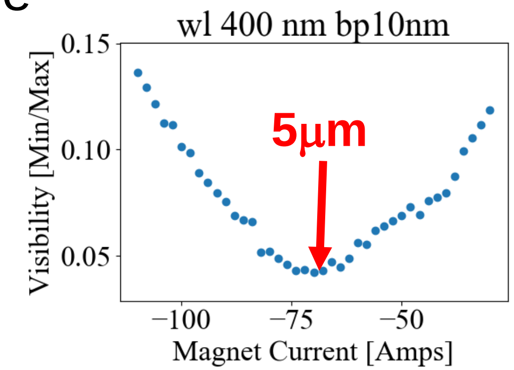


- Quadrupole scan down to 5μm beam size

<u>KEK-ATF2 target</u>

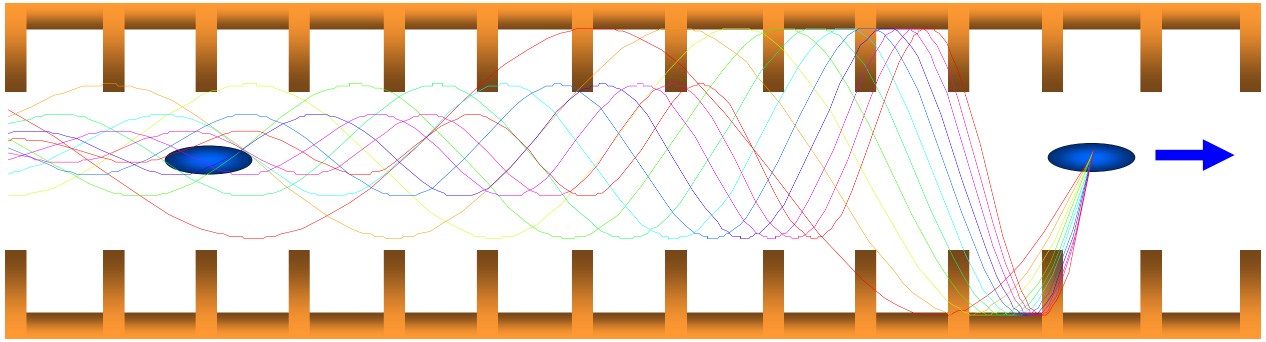
- 4 thin slits with an aluminum coating around them
- The rest of Target is sand-blasted





Conserving small Emittance along the Main Linac

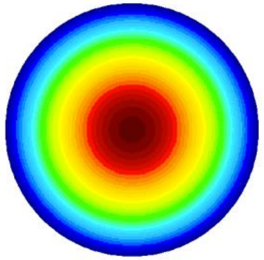
- **Minimizing offset in quadrupoles**
  - Beam based alignment to define a precise reference using **high resolution BPM** (50nm resolution – 4000 units along the linac)
  - Dispersion free-steering to align quadrupoles precisely



- **Minimizing wakefield in accelerating structures**
  - Structure design with passive damping of high order modes
  - Tolerances for structure's alignment down to 5μm
  - **Wakefield monitor** to measure the relative position of a cavity with respect to the beam

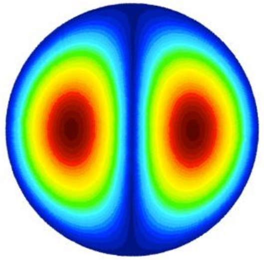
High resolution cavity BPM

- Resonant **‘Pillbox’ cavity** to measure the beam position
- Centered beam excites monopole mode (TM_{010}).
  - Amplitude dependent on charge

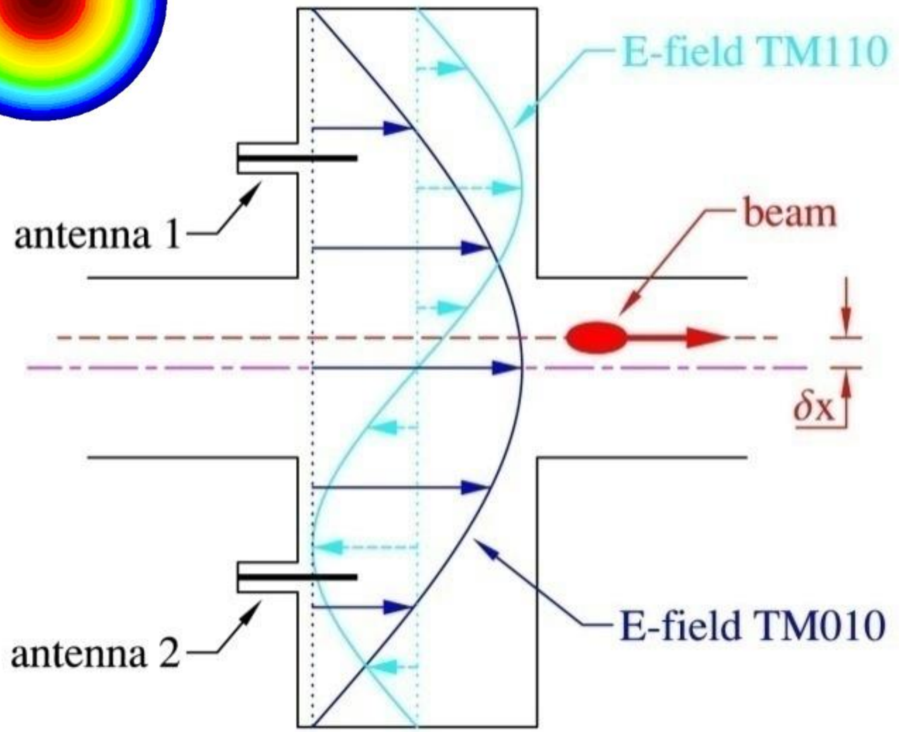


- Away from the center, other modes are excited.
  - First order dipole mode (TM_{110}) depends linearly on beam offset and charge.

$$V_{out} = \frac{\omega}{2}\sqrt{\frac{Z}{Q_{ext}}\left[\frac{R}{Q}\right]_0}\, q\, \frac{x}{x_0}$$

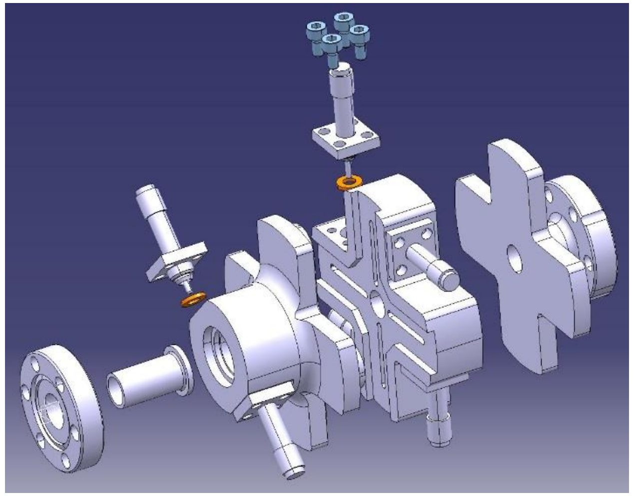


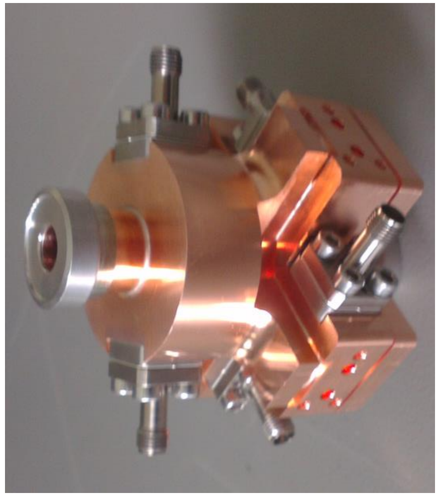
- TM_{110} splits in 2 orthogonal modes.
- Beam excites other unwanted higher order modes.
  - Requires suppression of unwanted modes.

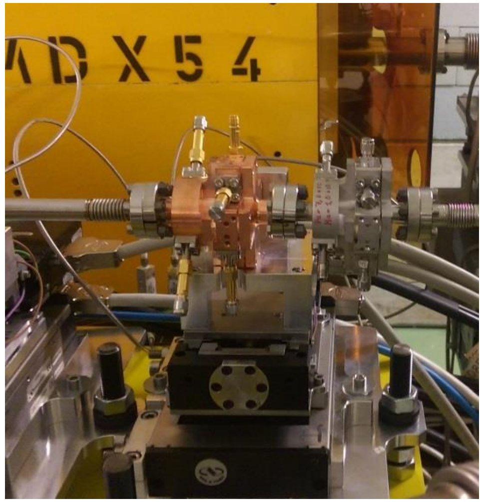


High resolution cavity BPM

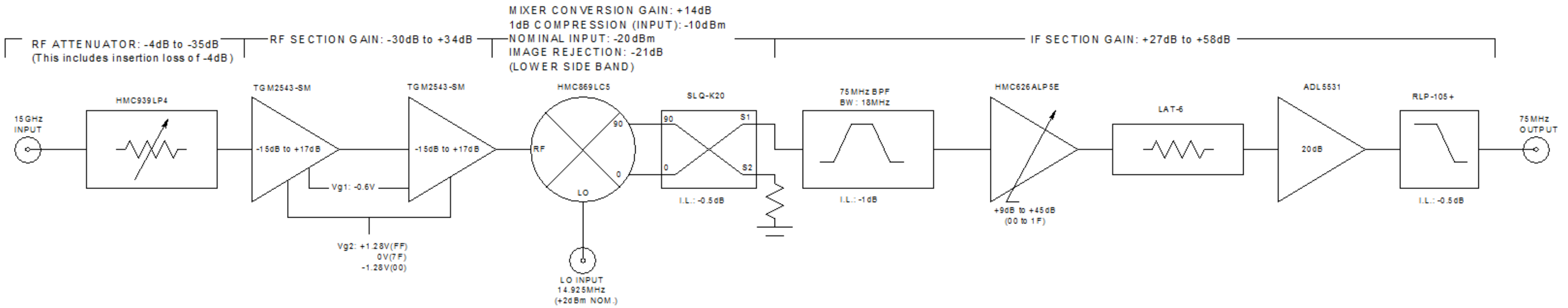
- Prototype of Cavity BPM for CLIC at 15GHz

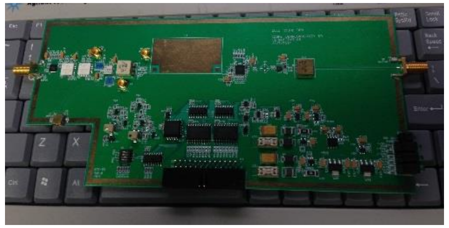




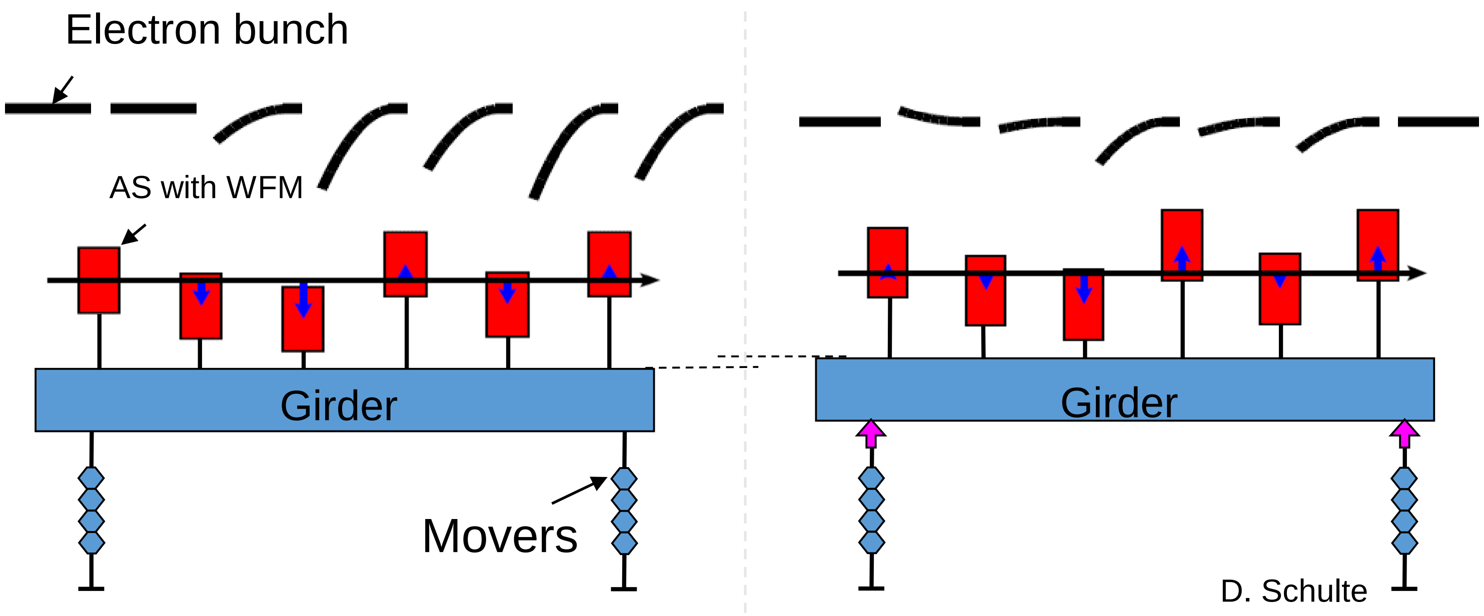


- Single stage down-converter electronics





Minimization of cavity wakefield effects

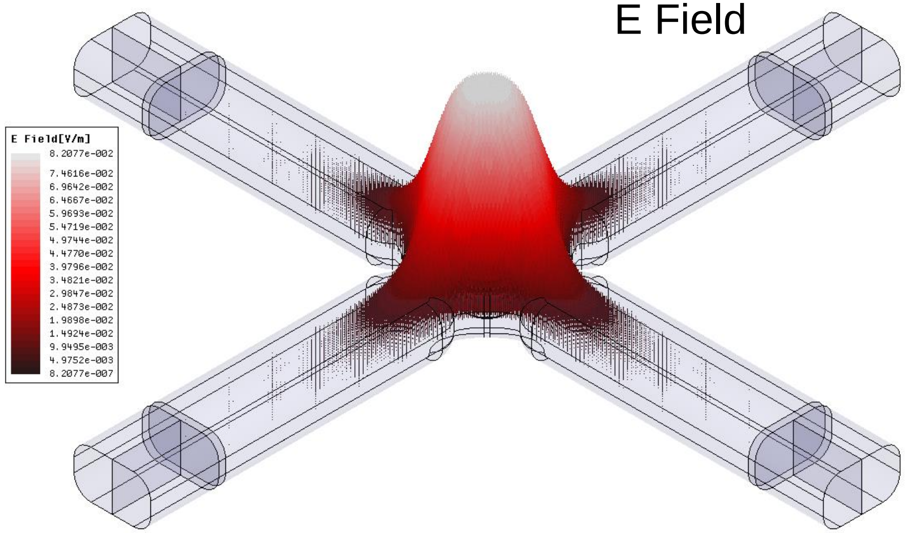


- Wakefield kicks from misaligned AS can be cancelled by another AS
- One WFM per 1-2 structure (142000 monitors) and mean offset of the 8 AS computed
- WFM with 5μm accuracy
- Need to get rid of the 100MW of RF power at 12GHz present in the structures

Wakefield Monitor design

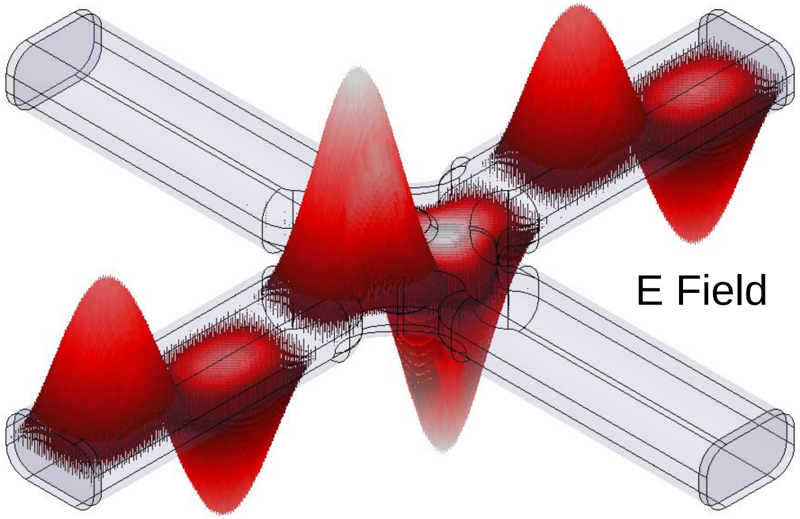
Monopole mode

E Field



Opposite ports signals
are in phase

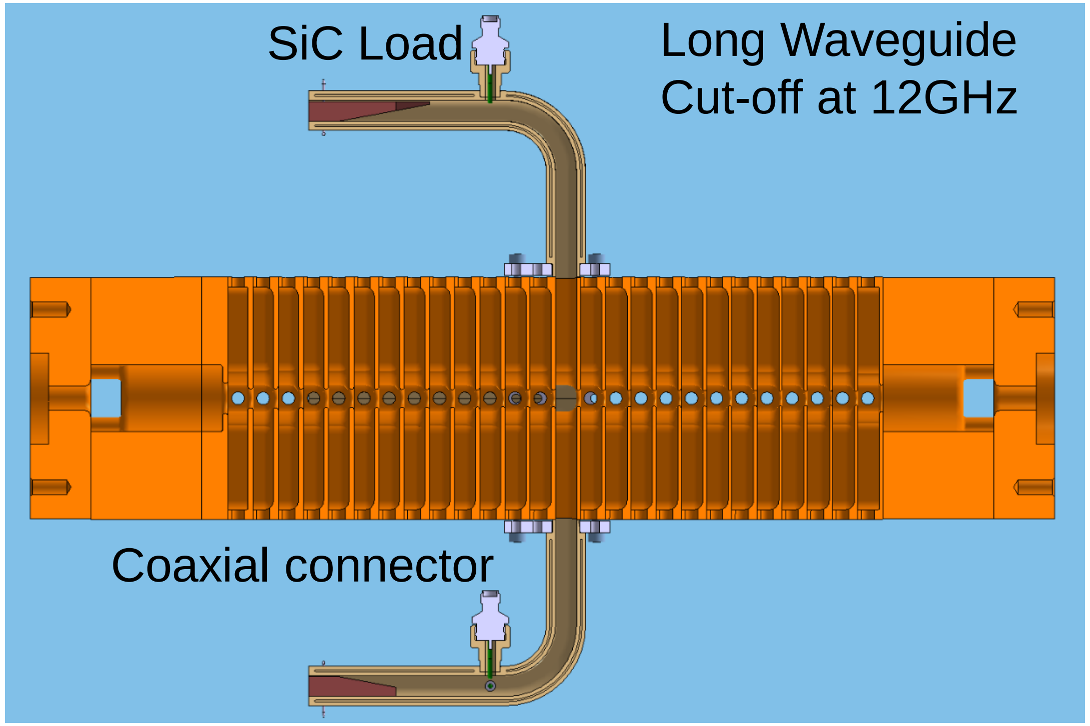
Dipole mode

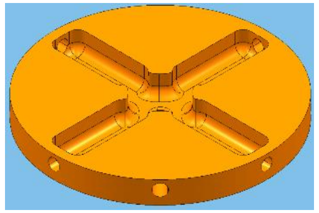


Opposite ports signal
have opposite phase

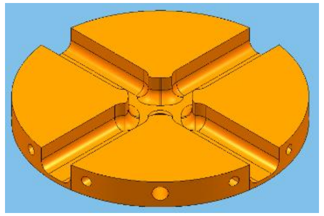
When we substract the opposite port signals, the monopole mode is cancelled and the dipole mode amplitude is increased

Wakefield Monitor design



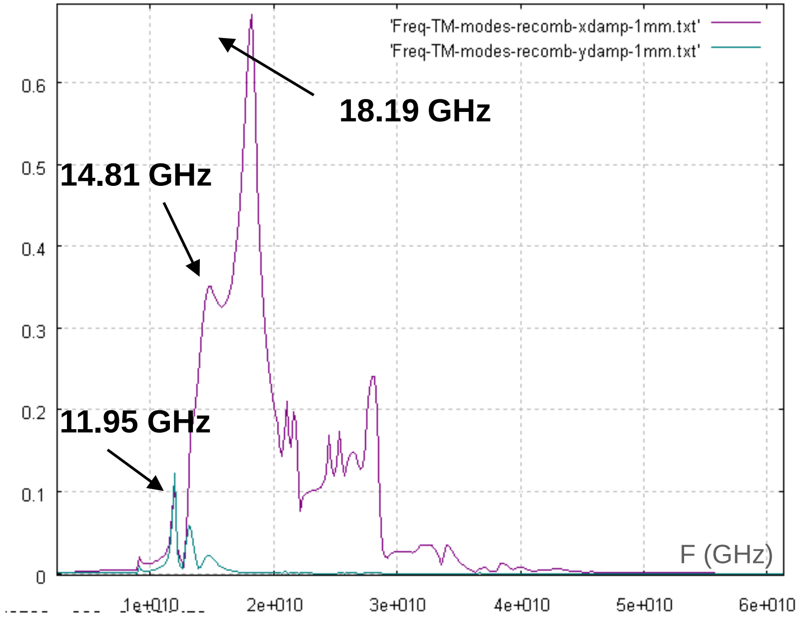


Regular cells with SiC load



Middle cell with WFM

Recombined port
signal amplitude



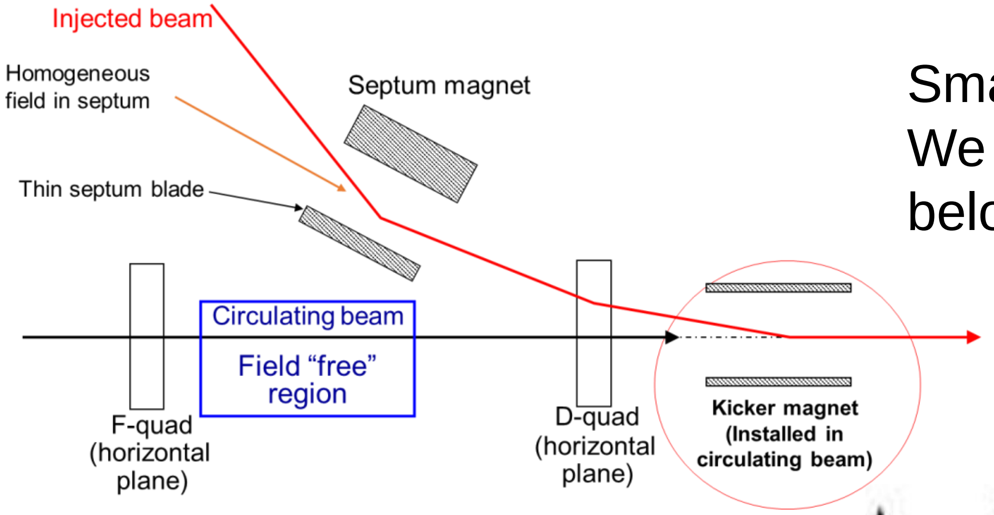
Similar electronics to the beam position monitor
Current studies in CLEAR to measure accuracy

Extraction kickers

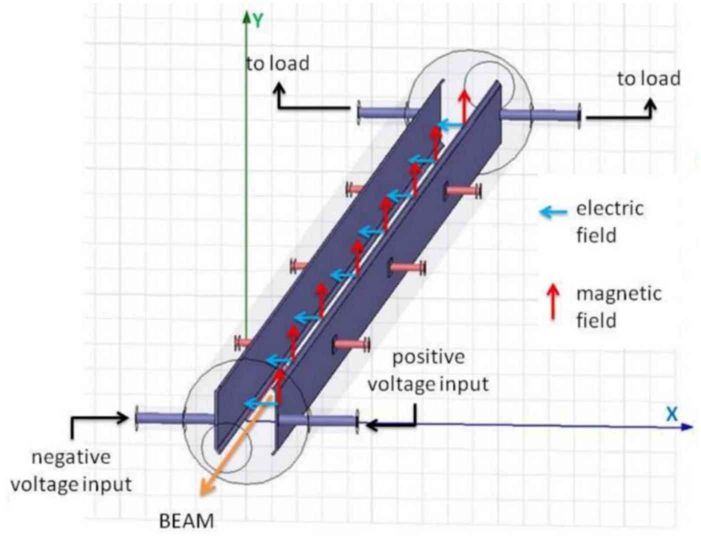
[Pulse Power Modulator development for the CLIC Damping Ring Kickers]

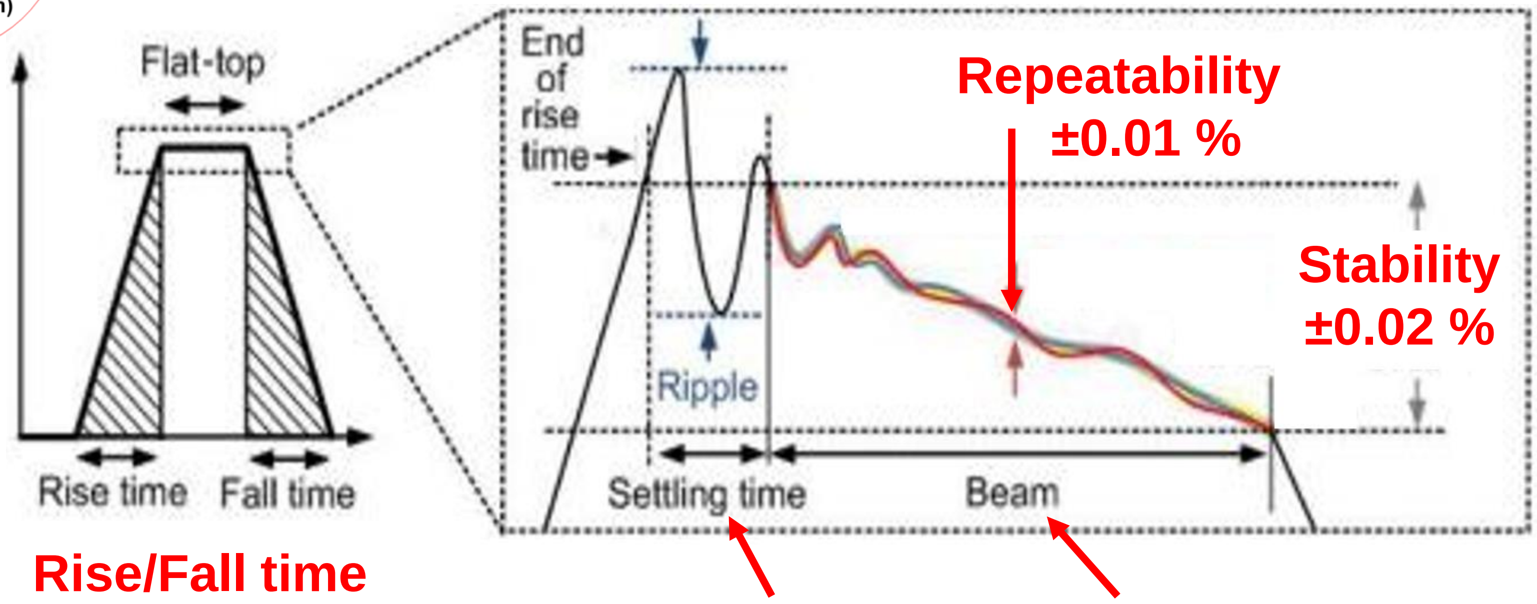
[Measurements on Magnetic Cores for Inductive Adders with Ultra-Flat Output Pulses for CLIC DR Kickers]

Specifications for the CLIC DR Extraction Kicker Pulse



Small beam sizes
We need to control the jitter of the beam at the exit of the DR below 10% of the beam size to conserve emittance





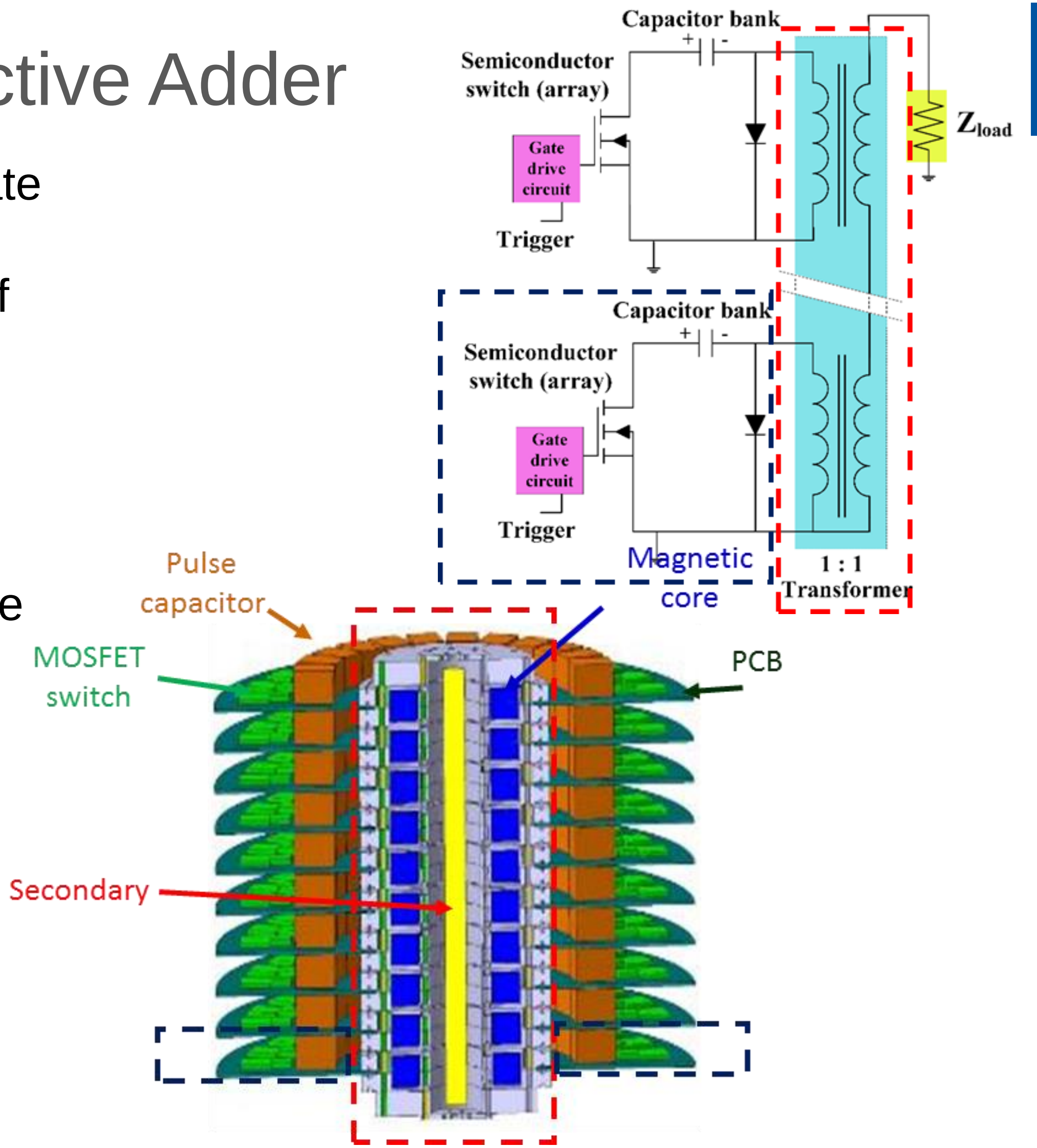
Rise/Fall time ~100 ns

Settling time ~100 ns

Flat-top duration 160 | 900 ns

Inductive Adder

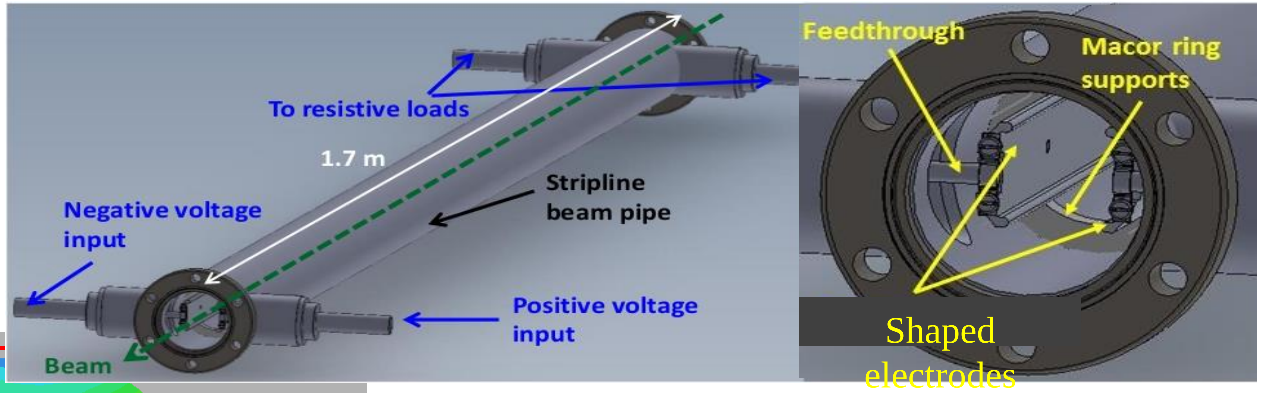
- Many primary “layers”, each with solid-state switches. The output voltage is (approximately) the sum of the voltages of the primary constant voltage layers
- The output voltage can be modulated during the pulse by passive/active analogue modulation.
- Possibility to generate positive or negative output pulses with the same adderAll control electronics referenced to ground potential.
- Built-in fault tolerance and redundancy
- Modularity: the same design can potentially be used for CLIC DR & PDR (12.5/17.5 kV)

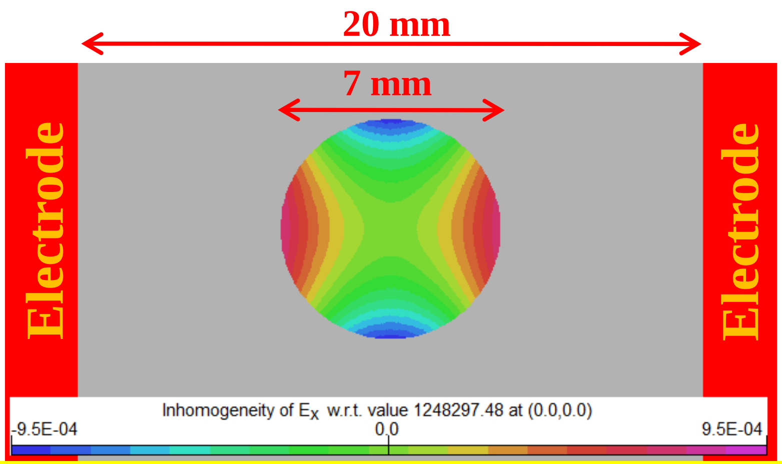


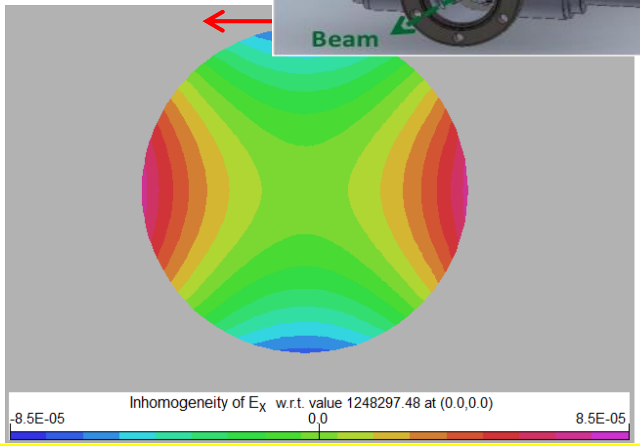
Stripline design: field homogeneity

CLIC Damping Ring (DR) specifications: Field inhomogeneity:

- ❖ **±0.1 %** (±1000 ppm) for DR injection (over 3.5 mm radius);
- ❖ **±0.01 %** (±100 ppm) for DR extraction (over 1 mm radius)
- ❖ low beam coupling impedance







Theoretically field homogeneity achieved – striplines installed at ALBA (ES) for measurements.

CLIC Magnet technologies

CLIC project R&D studies: the magnet system for the 3TeV. EDMS 1774039

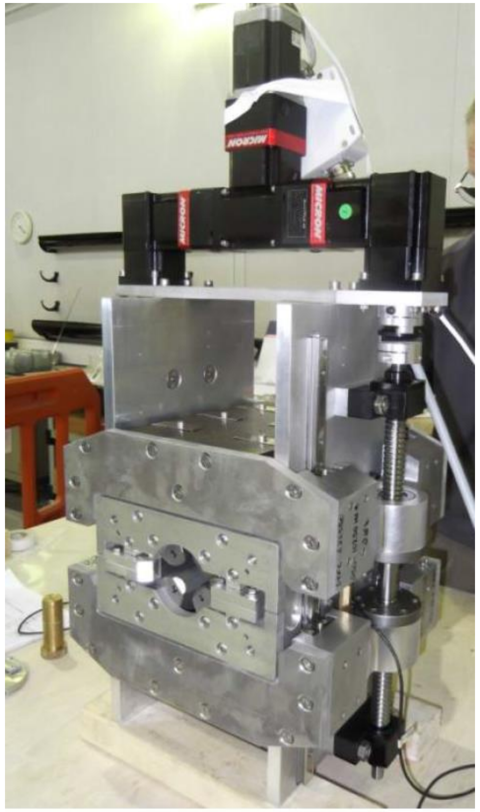
Design of Nb3Sn Wiggler Magnets for the Compact Linear Collider and Manufacturing of a Five-Coil Prototype

Longitudinally Variable Field Dipole Design Using Permanent Magnets For CLIC Damping Rings

Permanent magnets for power reduction

DRIVE BEAM

Type	Magnet type	Total	Effective Length [m]	H	V	Strength	Units	Min field	Max field	Rel Field Accuracy	Higher Harmonics [Tm]	per magnet [kW]	total [MW]
DBQ	Quadrupole	41400	0.194	26	26	62.78	T/m	10%	120%	1E-03	1.0E-04	0.5	17.0
MBTA	Dipole	576	1.5	40	40	1.6	T	10%	100%	1E-03	1.0E-04	21.6	12.4
MBCOTA	Dipole	1872	0.2	40	40	0.07	T	-100%	100%	1E-03	1.0E-03	0.3	0.5
QTA	Quadrupole	1872	0.5	40	40	14	T/m	10%	100%	1E-03	1.0E-04	2.0	3.7
SXTA	Sextupole	1152	0.2	40	40	85	T/m²	10%	100%	1E-03	1.0E-03	0.1	0.1
MB1	Dipole	184	1.5	80	80	1.6	T	10%	100%	1E-03	1.0E-04	42.0	7.7
MB2	Dipole	32	0.7	80	80	1.6	T	10%	100%	1E-03	1.0E-04	25.0	0.8
MB3	Dipole	236	1	80	80	0.26	T	10%	100%	1E-03	1.0E-04	4.5	1.1
MBCO	Dipole	1061	0.2	80	80	0.07	T	-100%	100%	1E-03	1.0E-03	0.4	0.4
Q1	Quadrupole	1061	0.5	80	80	14	T/m	10%	100%	1E-03	1.0E-04	5.9	6.3
SX	Sextupole	416	0.2	80	80	85	T/m²	10%	100%	1E-03	1.0E-03	0.5	0.2
SX2	Sextupole	236	0.5	80	80	360	T/m²	10%	100%	1E-03	1.0E-04	3.3	0.8
QLINAC	Quadrupole	1638	0.25	87	87	17	T/m	No data	100%	No data	No data	6.3	10.3
MBCO2	Dipole_CO	880	1	200	200	0.008	T	-100%	100%	2E-03	2.8E-05	0.3	0.3
Q4	Quadrupole	880	1	200	200	0.14	T/m	10%	100%	2E-03	2.8E-05	0.5	0.5

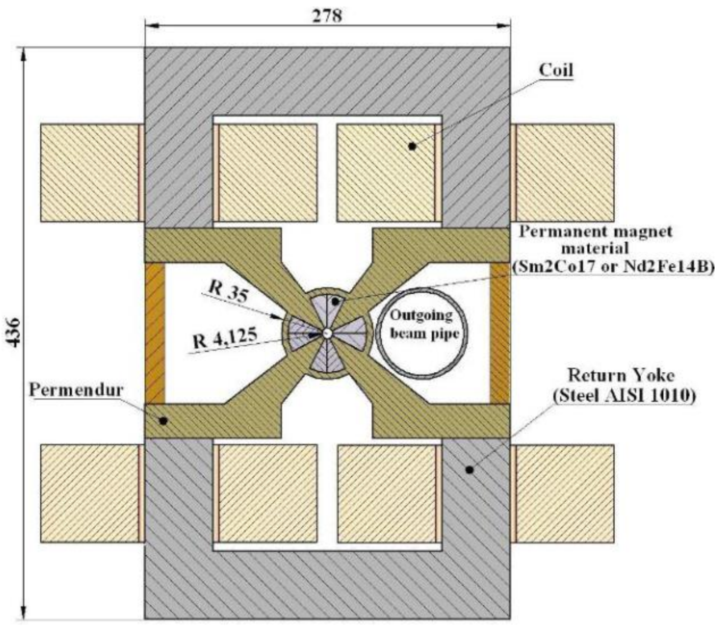


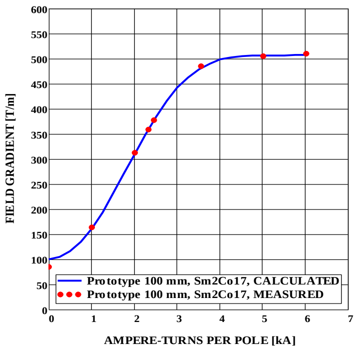
- Large power savings for large series of magnets
- Studies in Daresbury laboratory on DBQ and MBTA
- Permanent magnet technology for different energy ranges
- Tune-able through mechanical movement of te PM blocks
- Magnetic axes stability with varying gradient

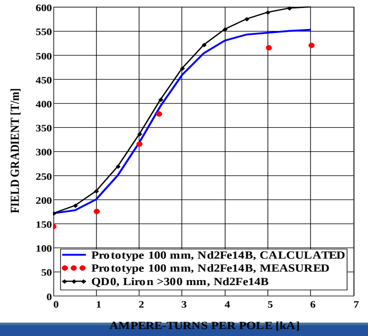
QDO short prototype

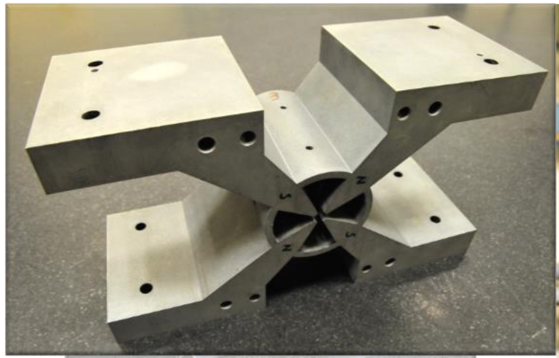
- Last quadrupole before the IP. Sits inside the detector
- Hybrid magnet using permanent magnets and electric-magnetic coil for tuneability.
- Need to stabilize the magnet to nanometre level.
- Water-free coils to avoid vibration
- Single piece in Permendur machined by EDM for high precision and magnetic quality
- Validated through Metrology and magnetic measurements

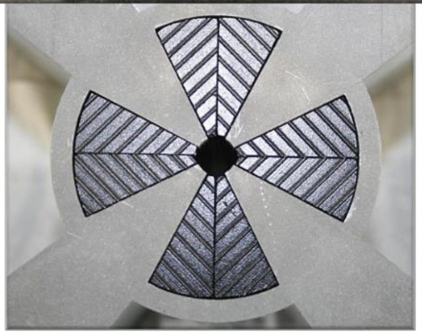
	Iw=5000 [A]
Grad [T/m] Sm_2Co_{17}	531
Grad [T/m] $Nd_2Fe_{14}B$	599

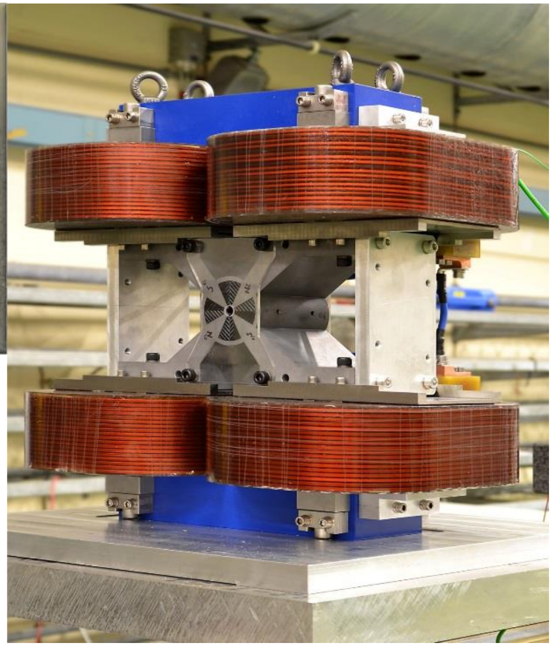




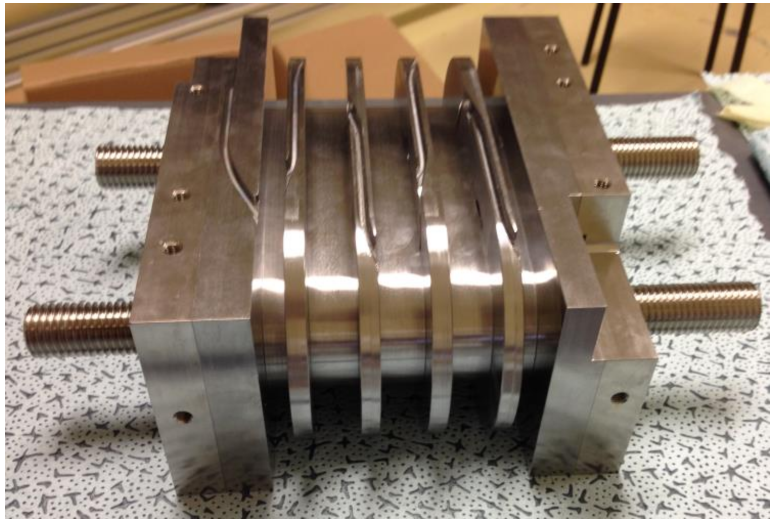


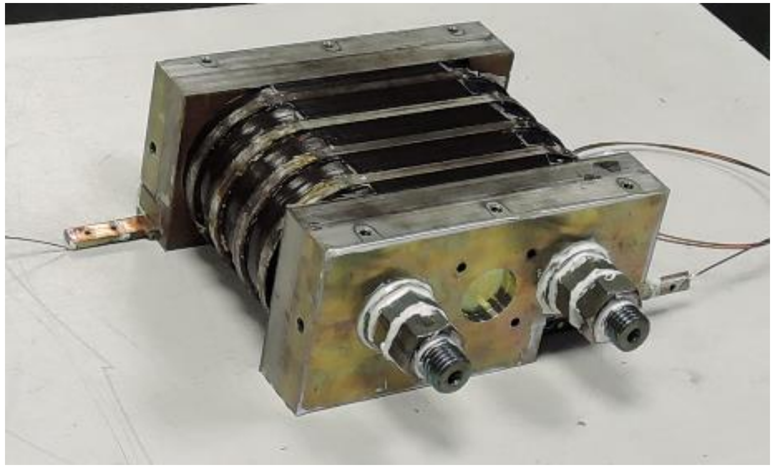




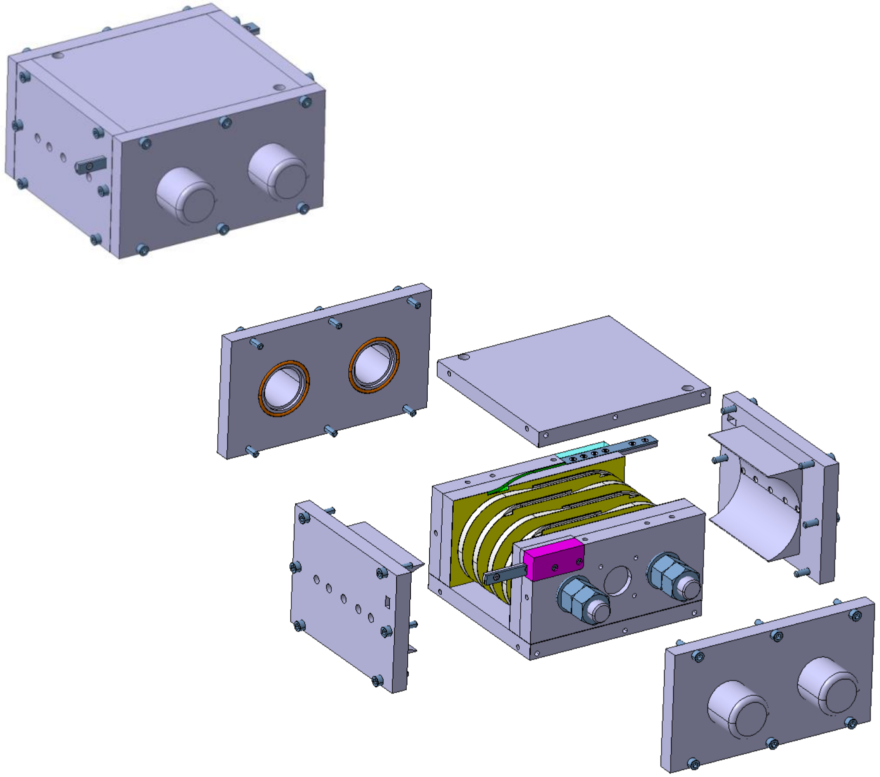


SC wigglers for the CLIC damping ring





- Emittance at the exit of the damping rings should be
  - 500nm horizontal
  - 5nm in the vertical plane.
- Using Nb3Sn Wigglers for the DR allows for a stronger field,
  - Less wigglers
  - shorter damping time,
  - Shorter ring
- Single strand Nb3Sn
- Short sample limit:
  - ~1100 A at 4.2 K
  - ~1200 A at 1.9 K
- Prototype manufactured
  - Under cold test in KIT

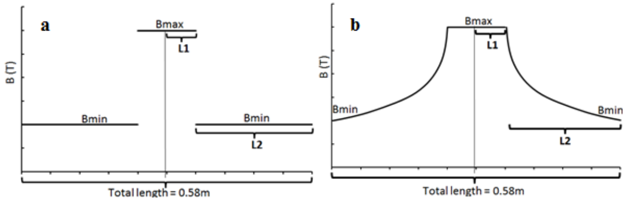


Longitudinal variable dipoles for the DR

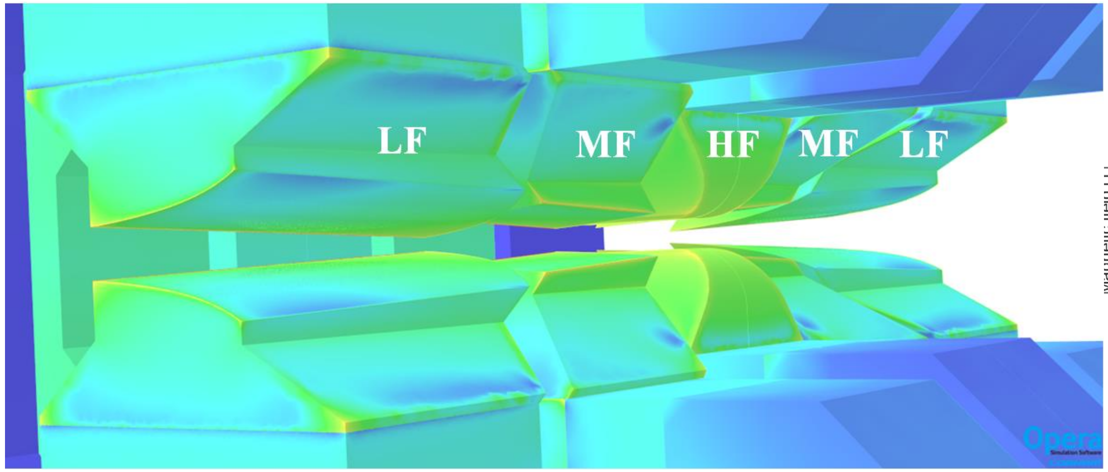
TABLE I
TECHNICAL SPECIFICATIONS

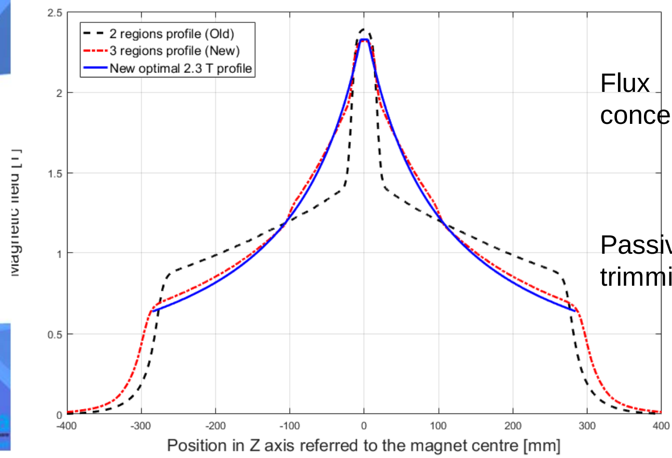
Good field region radius [mm]	5
Field harmonics [units 1E-4]	~1
Transverse gradient [T/m]	11
Magnet length [m]	0.58
Aperture diameter [mm]	13

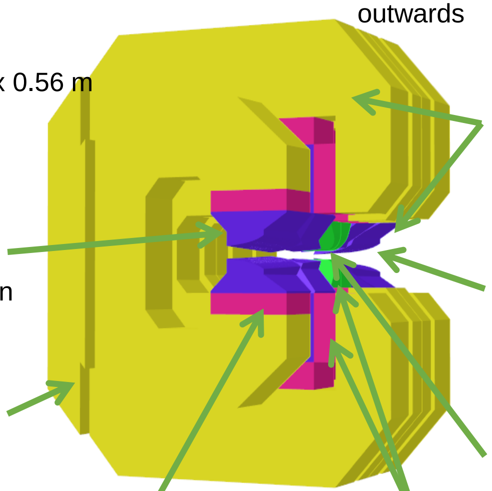
	Step profile	Trapezium profile Case 1	Trapezium profile Case 2	Trapezium profile Case 3
# of dipoles	96	90	90	90
Dip. field [T·m]	0.625	0.667	0.667	0.667
Bmax [T]	1.7666	1.7666	1.7666	1.7666
Bmin [T]	0.8737	0.7791	0.7508	0.7146
L1 [mm]	65.858	3.352	13.836	26.488
L2 [mm]	224.142	286.648	276.164	263.512



- Possibility to reduce the minimum emittance below the theoretical limit by the use of **longitudinal variable dipoles** with a trapezoidal profile
- Uses permanent magnets (both SmCo and NdFeB) in three different field regions
- Passive trimming of the total field foreseen by sectioning the return yoke.
- Mechanical design ongoing
- Prototype to follow







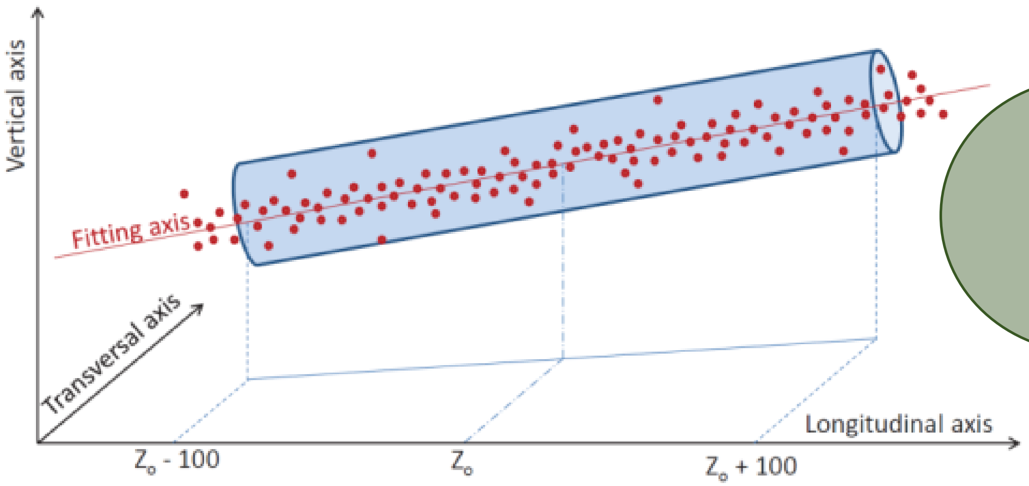
Alignment and stabilization

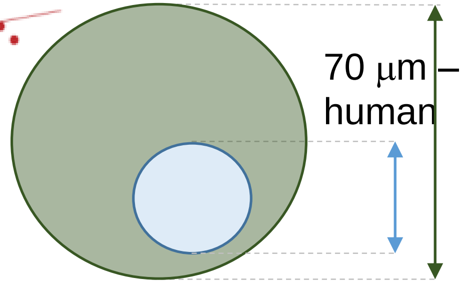
oWPS VERSUS cWPS

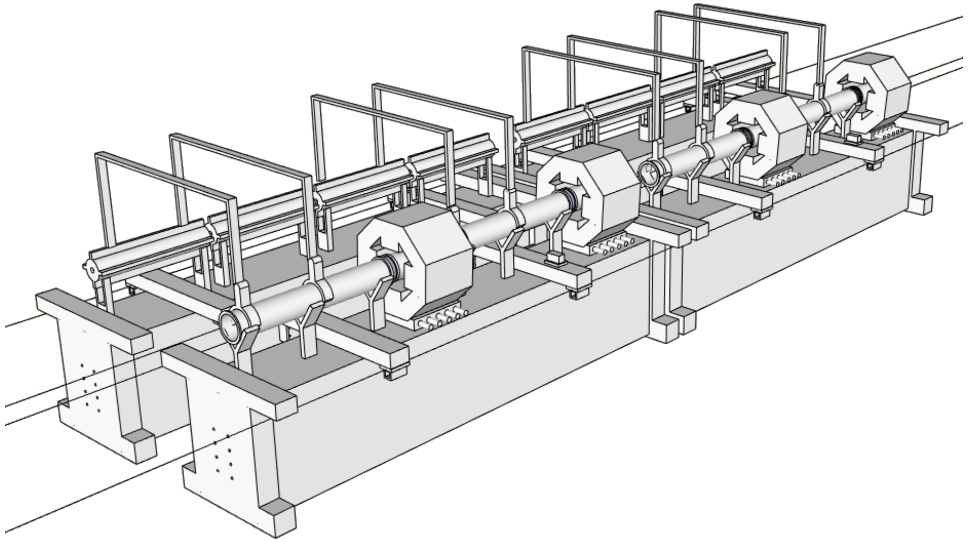
Micrometric propagation of error using overlapping stretched wires for the CLIC prealignment

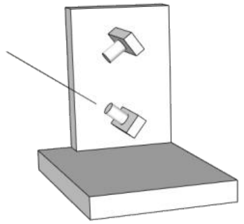
3rd PACMAN workshop

Alignment and fiducialization

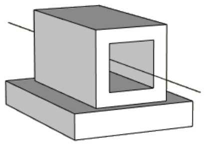




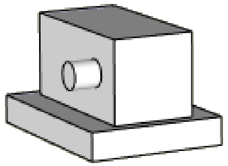




oWPS:
- Precision : 1 μm
- Accuracy : 10 μm
- Maximum 500 Gy



cWPS :
- Precision : 1 μm
- Accuracy : 5 μm
- Rad-Hard (5 MGy)



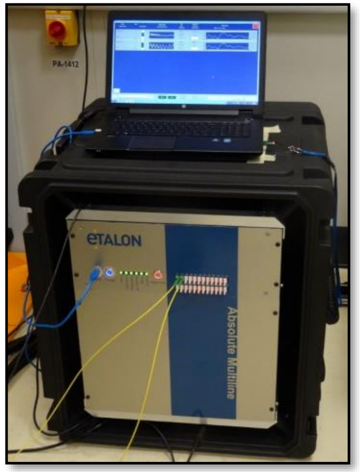
Tilt meter :
- Precision : 3 μrad
- Accuracy (1) : 60 μrad
- Accuracy (2) : 10 μrad
- Not Rad-Hard

imperfection	with respect to	symbol	value	emitt. growth
BPM offset	wire reference	σ_{BPM}	14 μm	0.367 nm
BPM resolution		σ_{res}	0.1 μm	0.04 nm
accelerating structure offset	girder axis	σ_4	10 μm	0.03 nm
accelerating structure tilt	girder axis	σ_t	200 $\mu radian$	0.38 nm
articulation point offset	wire reference	σ_5	12 μm	0.1 nm
girder end point	articulation point	σ_6	5 μm	0.02 nm
wake monitor	structure centre	σ_7	3.5 μm	0.54 nm
quadrupole roll	longitudinal axis	σ_r	100 $\mu radian$	≈ 0.12 nm

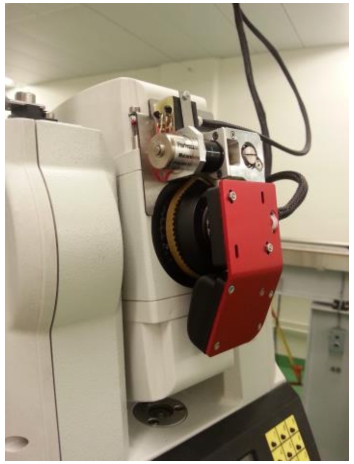
Medium and large metrology

- Keep the chain of measurement under the given requirements!
- Development of methods using Coordinate Measuring Machines Laser trackers laser scanner, portable CMM, tacheometer, Frequency scanning interferometry
- Development of new targets and reflectors
- Comertial and house-made alignment systems using linear actuators, cam movers, tables, stages
- Development of sensors, kinematic mounts, etc

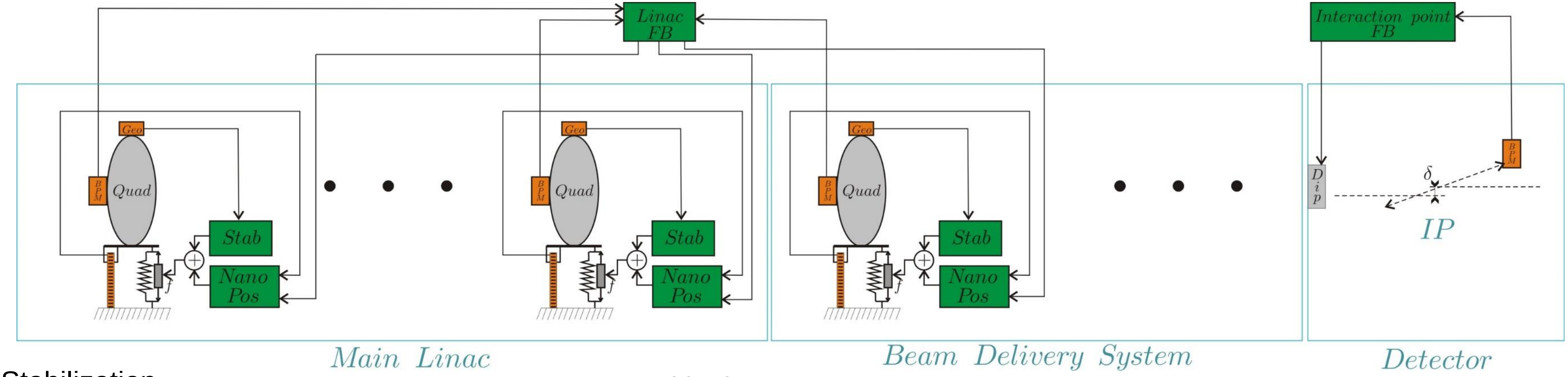
Proven in the module environment and in CTF3



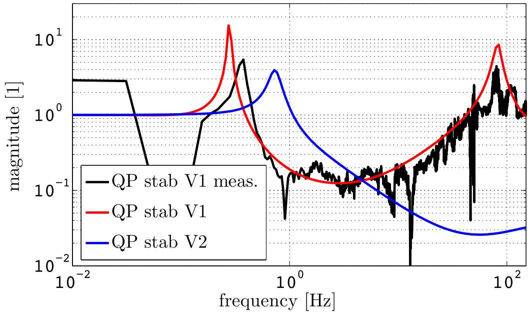




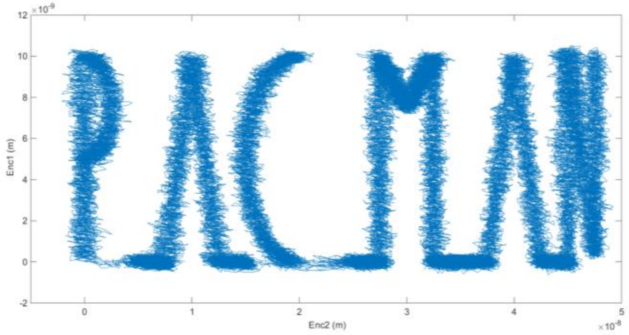

Stabilization and nano-positioning

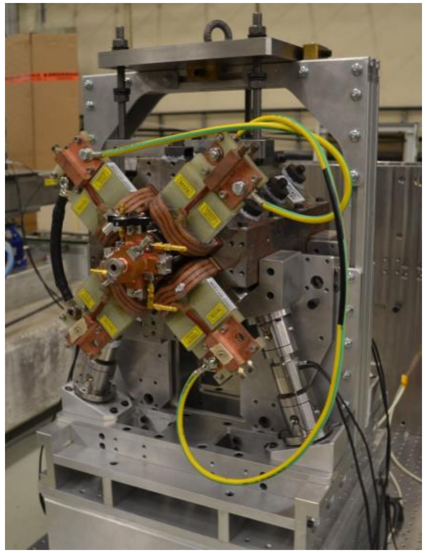


Stabilization
- Sensor: Inertial sensor (Geophone)
- Bandwidth:1 → 50 Hz
- Stability requirement: 1.5 nm rms @ 1 Hz



Nano-positioning
- Sensor: Linear encoder
- Positioning time: < 20 ms
- Displacement steps: up to 50 nm





Summary

- The requirements of CLIC push the established accelerator technology outside the beaten path
- All technology has been demonstrated as prototypes and tested
- Efforts are now concentrated on cost, reliability and industrialization
- Still lots of challenging hardware to design, manufacture and test!!

Much more material in CLIC past workshops and in the CDR!!

Thanks to all the CLIC team that knowingly or unknowingly provided me with material and specially to M. Barnes, J. Bauche, P. Ferracin, T. Lefevre, H, Mainaud Durand, M. Modena, Y. Papaphilippou and W. Wuensch

systems machining
Piezo klystrons based
gradient diagnostics packing nanometer
CLIC beam
atmosphere
power effort safety laser
bonding
required encoders Vibration
Technology milling Measuring
Coordinate voltage proven Precision
Typically
nm sintering
products furnace
fields
transfer thanks modulators
luminosity
mechanic
Diffusion test CMM tested metrology
vacuum capacitors
extension
protective tests wakefields unit
resolution
stiffness actuators brazing
Parallel
ceramics
stainless
Qualification sensors
Potential CERN
scanning interferometry
steel
technologies emittance Procurement