The CLIC Two-Beam Accelerator Module & Requirements

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for the CLIC Group

This presentation has been prepared with the help of

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Outline

- Two-Beam Module Description

- Module Design Process

- Module Subsystems: Status, Specifications and Requirements

Introduction

- CLIC is based on the two-beam acceleration concept

- To facilitate the matching of the two beams, all components are assembled in 2m long modules of few different types. The modules make use of girders to meet the pre-alignment requirements (smoothing of adjacent girders)

- Since each linac length is about 21 km, more than 10,000 modules are needed per linac

- The Module defines boundary conditions for technical solutions for important systems: AS, PETS, RF distribution network, stabilization, alignment, vacuum, … and has to cope with the challenging requirements from each of them

- It's a cost driver for CLIC, as well as a performance driver

≈ 2m

Two-Beam Module Design

- Longitudinal Requirements
    1. Physics -> Beam Dynamics <-> Acc. Structures Design
    2. PETS Design and Optimization
    3. Module Layout

- Transverse Requirements
    1. Stabilization
    2. Instrumentation
    3. Cooling
    4. Vacuum, …

Two-Beam Module Design Chart

Luminosity per linac input power

$$\frac{L}{P_l} = \frac{L_{b\times}N_b f_{rep}}{\dfrac{eE_c N N_b f_{rep}}{\eta}} = \frac{1}{eE_{cm}} \cdot \frac{L_{b\times}}{N}\eta$$

BD <-> AC design

Beam dynamics (BD) constraints based on the simulation of the main linac, BDS and beam-beam collision at the IP:

- N – bunch population depends on $<a>/\lambda$, $\Delta a/<a>$, f and $<E_a>$ because of short-range wakes
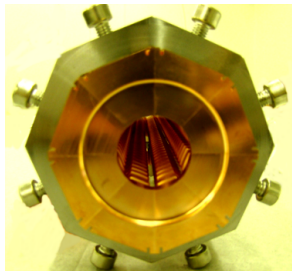- N_s – bunch separation depends on the long-range dipole wake

PETS design

- Drive beam current and energy
- RF power production needs
- Beam transport and stability
- Module layout and fabrication technology
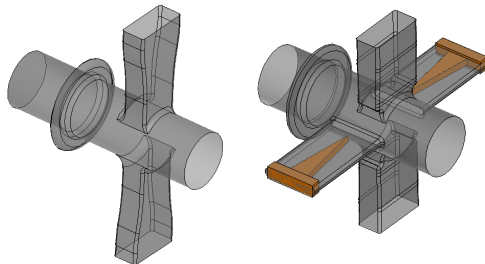- Power extraction and transfer

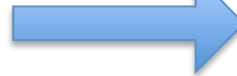RF breakdown and pulsed surface heating constraints
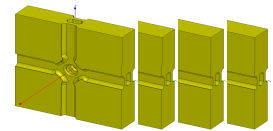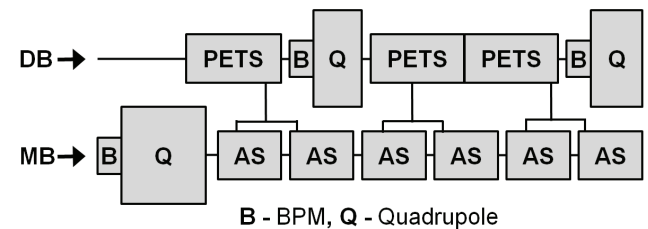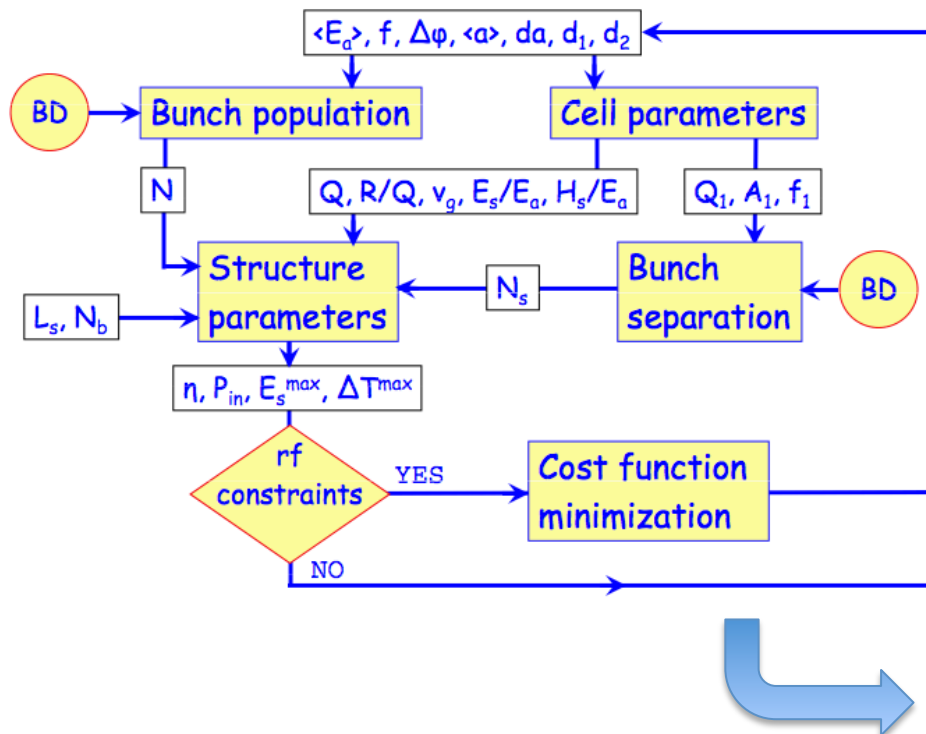

AS cells

Pre-assembled PETS

RF power extractors

Two-Beam Module Layout

B - BPM, Q - Quadrupole

(1) Accelerating Structure Optimization

CLIC Main Linac Parameters

Parameter	Symbol	Value	Units
Energy CM	E_{cm}	3000	GeV
Luminosity	$L_{99\%}$	2	$10^{34} cm^{-2} s^{-1}$
RF freq	f_{RF}	11.994	GHz
Repetition Rate	f_{rep}	50	Hz
Bunch population	N_b	3.72	10^9

Accelerating Structure Parameters

Structure	CLIC_G
Frequency: f [GHz]	12
Gradient [MV/m]	100
Average iris radius/wavelength: $\langle a \rangle / \lambda$	0.11
Input/Output iris radii: $a_{1,2}$ [mm]	3.15, 2.35
Input/Output iris thickness: $d_{1,2}$ [mm]	1.67, 1.00
Group velocity: $v_g^{(1,2)}/c$ [%]	1.66, 0.83
N. of reg. cells, str. length: N_c, l [mm]	24, 229
Bunch separation: N_s [rf cycles]	6
Number of bunches in a train: N_b	312
Pulse length, rise time: τ_p, τ_r [ns]	240.8, 22.4
Input power: P_{in} [MW]	63.8
Max. surface field: E_{surf}^{max} [MV/m]	245
Max. temperature rise: ΔT^{max} [K]	53
Efficiency: η [%]	27.7
Luminosity per bunch X-ing: L_{bx} [m^{-2}]	1.22×10^{34}
Bunch population: N	3.72×10^9
Figure of merit: $\eta L_{bx}/N$ [a.u.]	9.1

Courtesy of **A. Grudiev**

(2) PETS Design Development Chart
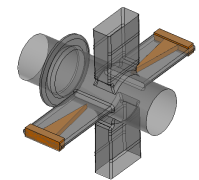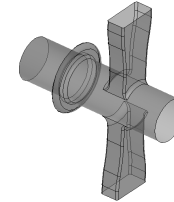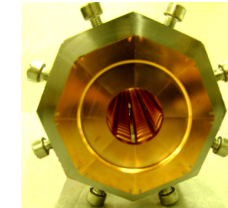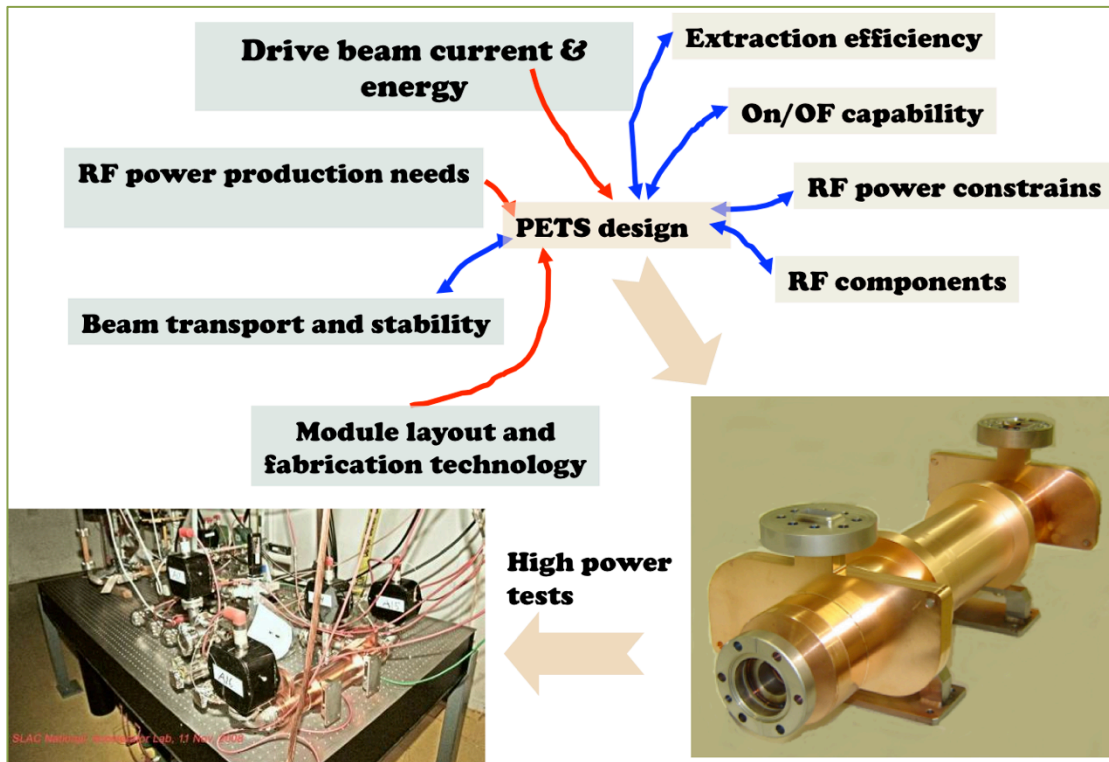
Table 3: The 12 GHz CLIC PETS parameters.

|	
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}

Courtesy of **I. Syratchev**
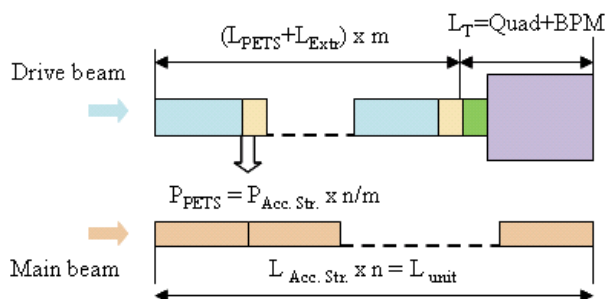
Module Parameters & Layout

Each module has a length multiple of two sets of PETS and 1 drive beam (DB) quad. Each PETS feeds 2 AS. As a result of this, the length of the CLIC Module is obtained as

$$L_{module} = L_{acc} \times 8 + L_{int} = (250 \times 8 + 10) \text{ mm} = 2010 \text{ mm}$$

	Act. Length [mm]	Aperture [mm]	Gradient [MV/m]	Power [MW]
PETS	213	23	6.5	133.7
AS	229	5	100	63.8

Parameter	3 TeV	Unit
Module length	2010	mm
Length of PETS w/couplers	308	mm
PETS tolerance (1σ)	31	μm
Number of AS (in Module Type-I)	6	-
Length of AS	250	mm
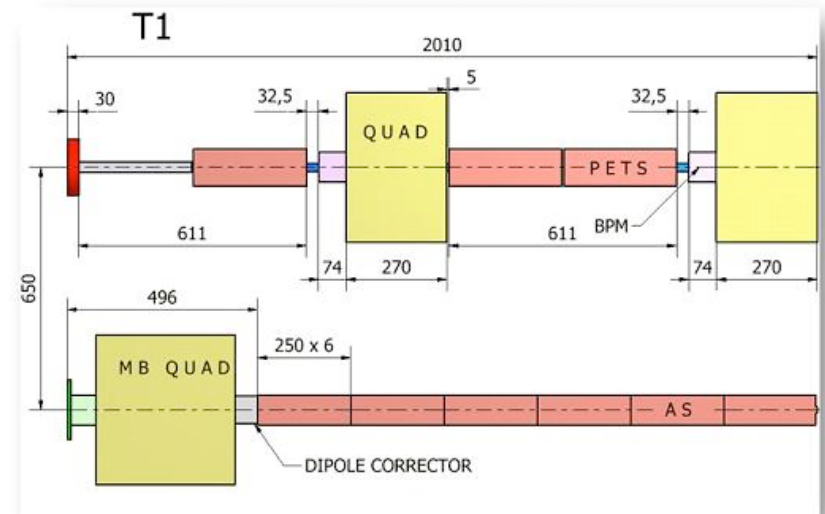
There are five Types of Modules: ``Type-?'' depending on the number of MB quadrupoles

Two-Beam Module Type-I

Courtesy of **A. Samoshkin**, see **G. Riddone's** talk
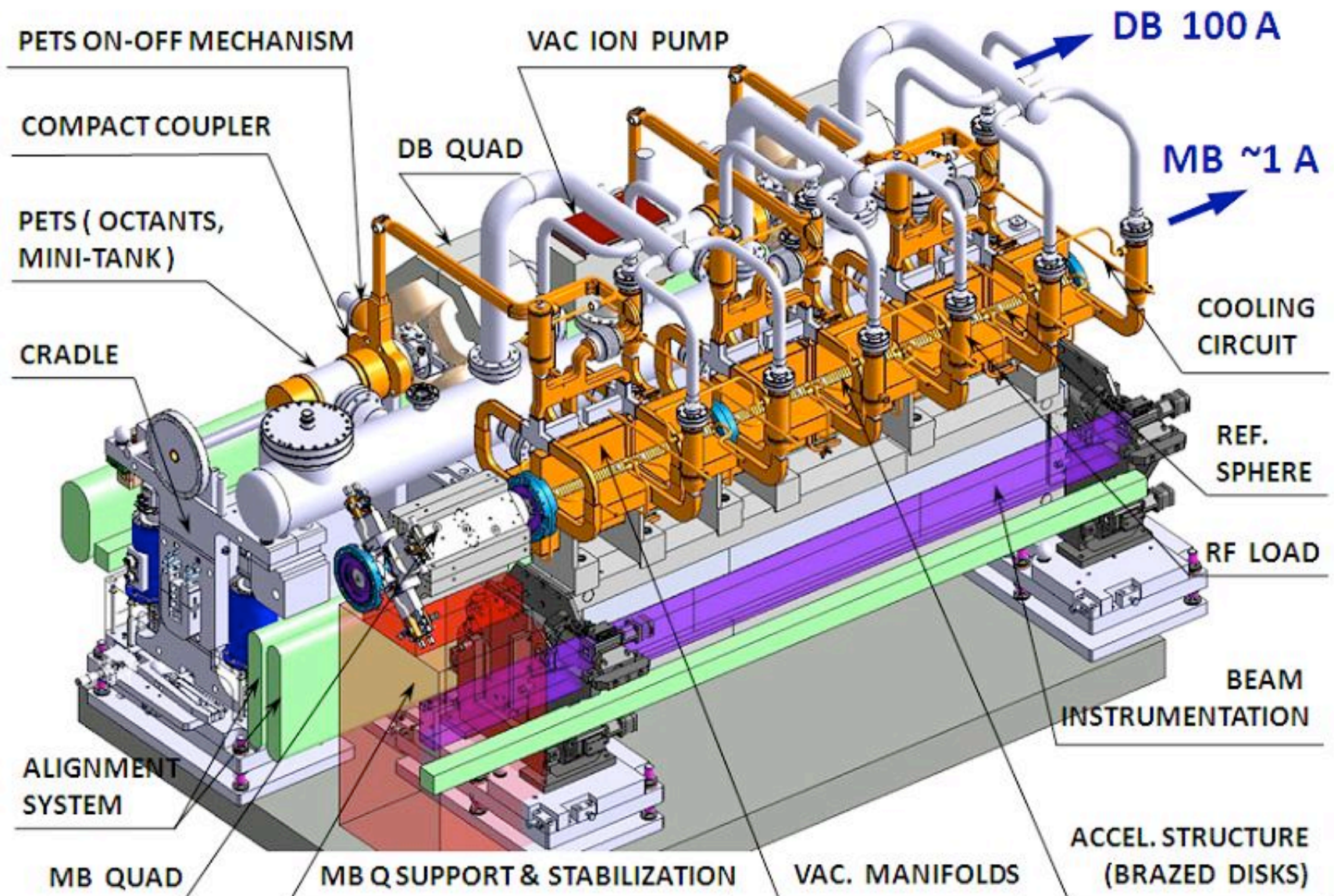
Module RF Network

- The RF system comprises the connection between the PETS and ACS and then from the ACS to the high power loads.

CMF - choke mode flange, H - compact E-hybrid,
C - compact coupler, L - rf load, WFM - wake field monitor
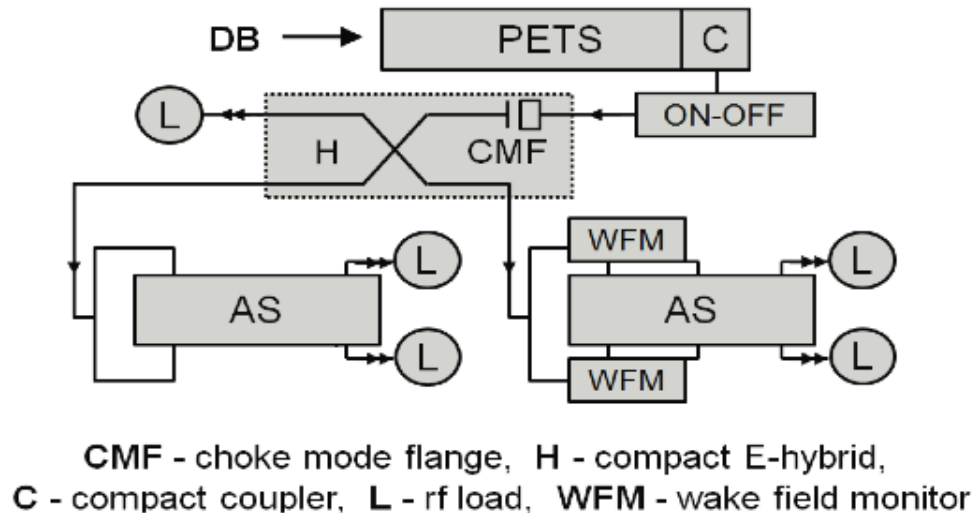
- The two-beam RF network includes the X-band rectangular wave-guides providing connection between PETS, AC and other supplementary devices.

- It's necessary to join the PETS outgoing waves by one channel. Because of the limited longitudinal space a compact coupler is needed.

- In case of a breakdown in a AS it is necessary to interrupt the power produced by the corresponding PETS within 20 ms. "On-Off" mechanism

Module RF Network
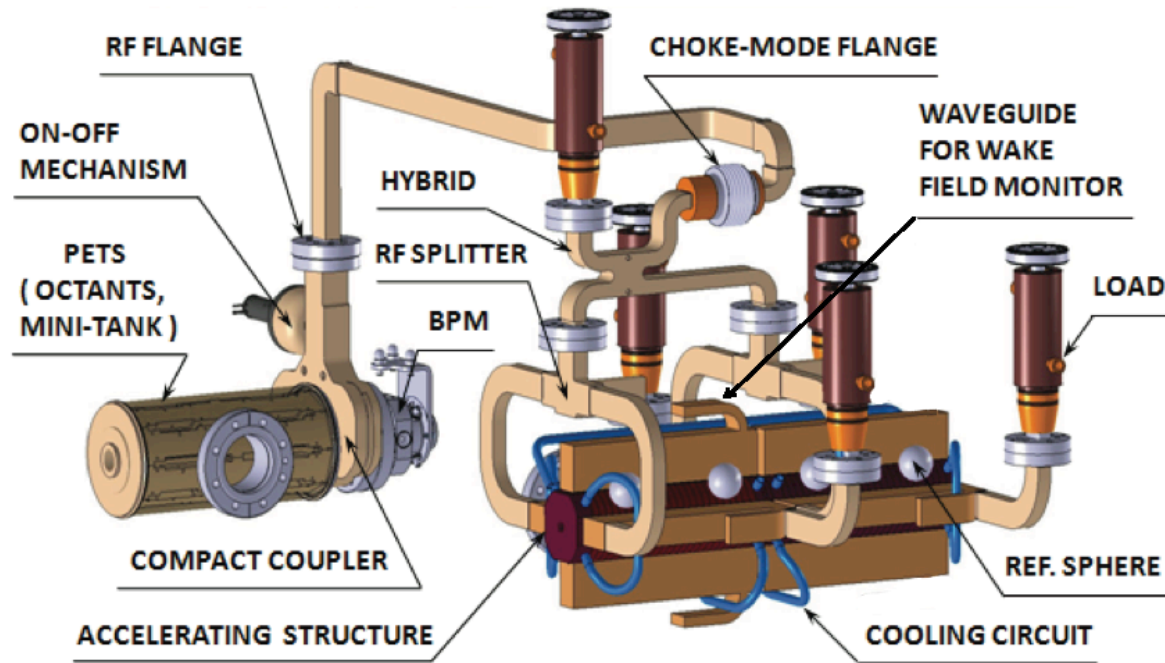
- Another requirement is to guarantee transverse alignment flexibility between the two beams and thus to allow for the power transmission without electrical contact

- Another necessity is to have a split of power between two AS without any reflection to the feeding PETS in a broad frequency range

- The power delivered from PETS to the two fed AS must be **synchronized in phase**

Main Beam RF Diagnostics

General layout in a DB Sector (~800m)
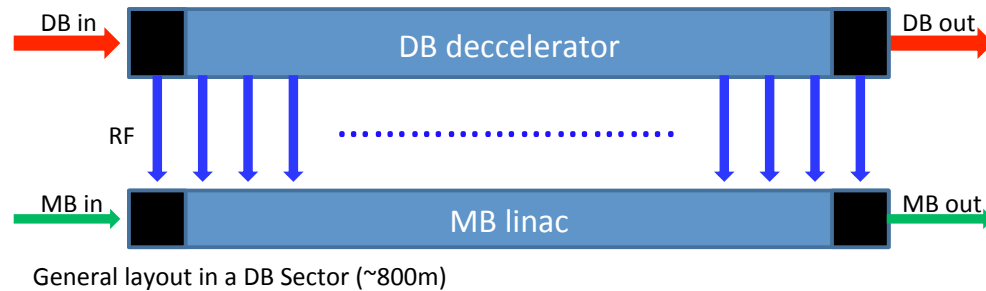
Two types of PETS+2AS units will be installed:

1. Reference **(black)** (2 units at the beginning and 2 units at the end of a DB sector)
    *   It will have more signals and with higher resolution
    *   The signals will be time resolved: dt ~ 0.5 ns (pulse shape)

2. Regular **(blue)** (all the rest)
    *   It will have 1 or 2 signals
    *   Integral over the pulse (1 or 2 numbers per pulse)

PETS+2AS unit: Reference
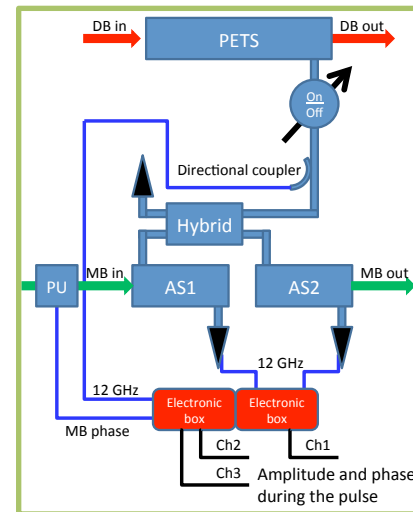
PETS+2AS unit: Regular
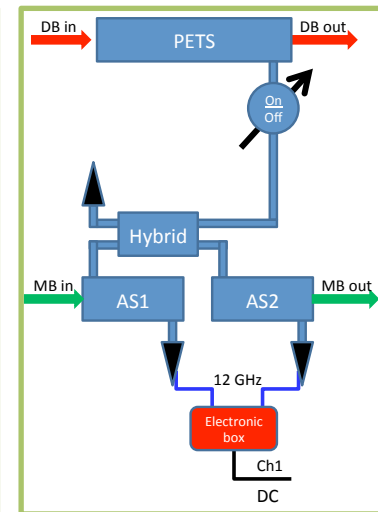
*   RF diagnostic
    1. RF breakdown in PETS and AS
    2. PETS on/off failure
    3. Provide references for the regular PETS+2AS units
*   Beam control
    1. RF power production
    2. Energy measurement and beam loading transient compensation

1. RF breakdown
2. PETS on/off failure

Courtesy of **A. Grudiev**

WakeField Monitors

Position monitors called Wakefield Monitors (WFM) are integrated to the structure for beam-based alignment (cost saving solution). There will be 1 WFM for each super-structure.

To achieve the target luminosity, the accelerating structures must be aligned to an accuracy of **3.5 µm** with respect to the beam trajectory.

TBTS WakeField Monitor Prototype

Beam-based alignment of the cavities
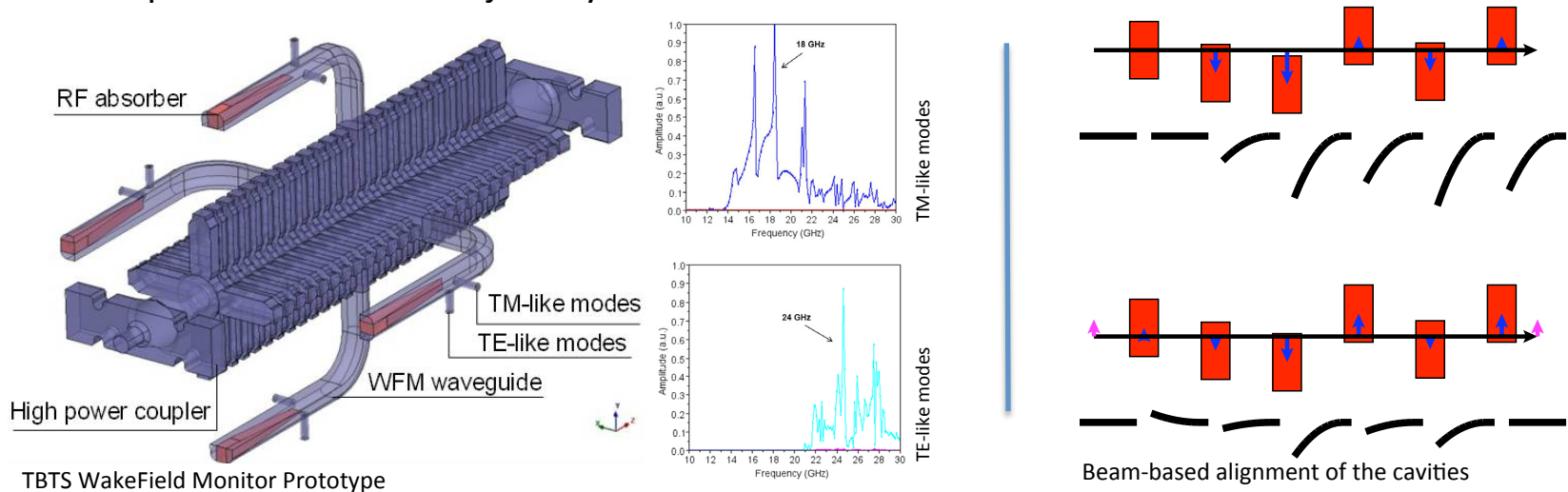
The alignment of the accelerating structures in the CLIC main linac is necessary to remove the wakefield effects on the beam.

Simulations moving the articulation points showed that the emittance growth can be very well improved by aligning the accelerating structures to an accuracy of 3.5 µm

For our tolerance σ_{WFM} = 3.5 µm, we found $\Delta\varepsilon_y \approx 0.5$ nm.

Supporting Girders & Active-Pre Alignment

The pre-alignment of CLIC will have to guarantee a tolerance on the transverse positions of the girders of ± 10 μm (1σ) on a sliding window of 200m.

- A simplification of the problem is to pre-align a number of components of each linac on girders, i.e. align the girders instead of aligning each of the components

≈ 2m

Adjacent girders linked by a common articulation point

- A simplification of the alignment by linking all the adjacent girders by a common articulation point. The alignment then consists in aligning each articulation point according to three degrees of freedom

Adjacent girders linked by a common articulation point

See talk by **H. Mainaud Durand**
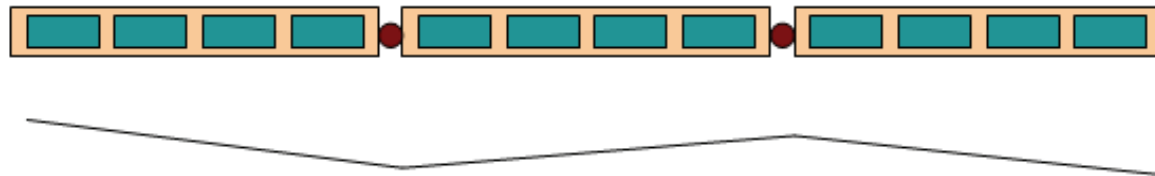
Supporting Girders

- The module design is based on a **common girder that supports the components of each different system**: such as AS, vacuum manifolds, RF components, PETS with their compact couplers, "On-Off" mechanism, vacuum connections as well as the DB quadrupoles equipped with BPM

- The girders should provide a sufficient **mechanical stability** and assure **continuity** for the chain of components of one beam

- The main components of each beam must be properly aligned to cope with beam and RF requirements

- The **MB Q** must stay independent of other components and such **require the self-governing supports**, which should combine both alignment and stabilization functions. Five degrees of freedom

See talk by **H. Mainaud Durand**

Pre-Alignment & Stabilization Requirements

Main alignment requirements in the vertical plane

Component	Tolerance (1σ)
Accelerating Structures	14 μm
PETS	31 μm
Main beam quadrupoles	17 μm
BPM for main beam quadrupole	14 μm
Relative position of MB quad. and BPM	5 μm

- The **AS** are the **most sensitive components**

- The **stabilization system** is required for the **MB quadrupoles only**

- The quadrupole support has **five degrees of freedom**, to be adjusted coherently with the other MB components

- A high mechanical stability is required for the MB quadrupoles: the requirement is not to exceed 1 nm in the vertical plane and 5 nm in the horizontal plane, for frequencies higher than 1 Hz. Two solutions are being studied at this purpose: **active stabilization** with nano-alignment between pulses; another is a combination of **passive and active isolation**

- The alignment of the **AS** is achieved through **WF monitors**

See talk by **D. Schulte**

Active Pre-alignment

Mechanical pre-alignment

Within +/- 0.1 mm (1s)

Active pre-alignment

Within ± 3 mm (1s)

Beam based alignment:

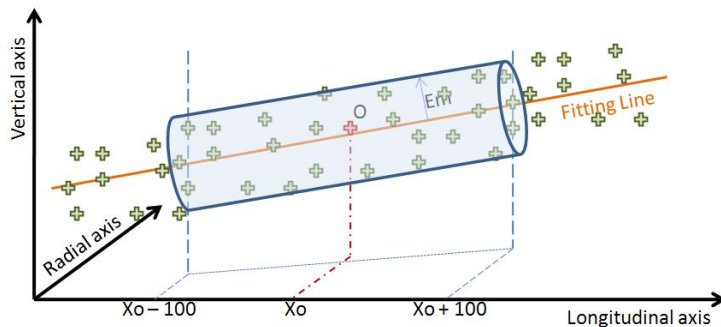1:1, DFS, RF AS Alignment

Beam based feedbacks

Active pre-alignment   =   Determination of the position of the components in a general coordinate system thanks to alignment systems

+

Re-adjustment thanks to actuators

After computation, for a sliding window of 200 m, the standard deviations of the transverse position of the zero of each component w.r.t a straight fitting line will be included in a cylinder with a radius of a few microns:

→ 14 μm (RF structures & MB quad BPM)

→ 17 μm (MB quad)

Adjustment: step size of the order of 1 μm

Vertical axis

Radial axis

Fitting Line

Xo − 100   Xo   Xo + 100   Longitudinal axis

Courtesy of **H. Mainaud Durand**

Main Linac Mover Tolerances

- Coarse mechanical motion
  - girders, MB quadrupoles supports
  - range: ≈ 1 mm
  - resolution: Δ ≈ 1 μm
  - precision: ≈ 0.5 μm
  - speed: may take a few pulses, but controlled

- Fine quadrupole motion
  - resolution: Δ ≈ 5 nm
  - range: ≈ 20 μm
  - precision: ≈ 2 nm
  - speed: from pulse to pulse

- Very fine quadrupole motion (stabilization system)
  - resolution: Δ order of ≈ 0.1 nm
  - range and precision: site dependent
  - speed: works in interval between pulses

See talk by **D. Schulte**

Main Beam Quadrupoles

There are 4 types of MB quadrupoles. They are different only for the active (magnetic) length, keeping all the cross-section dimensions and operational parameters identical.

Types	Mag. Length	Units
Type-1	35 cm	308
Type-2	85 cm	1268
Type-3	135 cm	953
Type-4	185 cm	1462
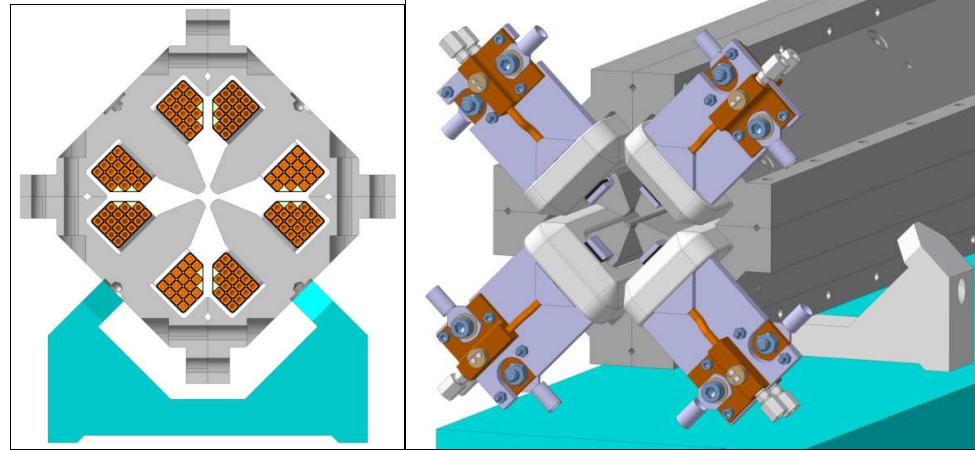
Cross-section and Extremities view of the MB Quadrupoles

Some of the quadrupoles are 2 m long and weight about 450 kg.

- A **beam steering** capability is required along the Main Beams
- The required steering capability is asked in one plane per magnet alternatively.
- Two main solutions are being considered : a MBQ built-in correction scheme with extra-coils in each magnet (a) or an "ad hoc" <u>small dipole corrector to be added to each MBQ</u> (b).

(a)   (b)
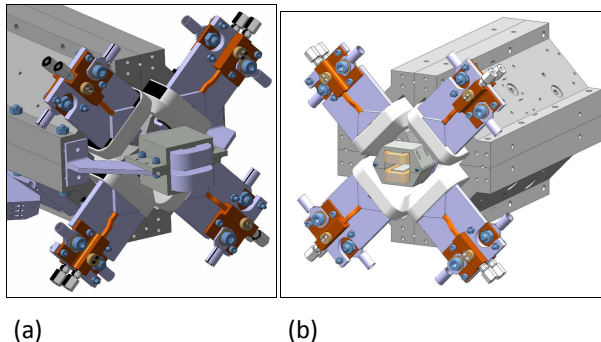
View of the Beam Steering Corrector integration for the MBQ Type-4 (a) and Type-1 (b)

Courtesy of **M. Modena**

Drive Beam Quadrupoles

- DB quadrupoles are present all along the beam in a FODO configuration with one F and one D quadrupole on each Module.

- Decelerators are so characterized by the presence of 20740 quadrupoles on each linac.

- Specification: one quadrupole per meter gives beta function (for most decelerated particles) of $<\beta> = 1.25$ m
  - Deemed necessary for robust mitigation of dipole wake
  - Gives r = 3.3 mm (out of a_0 = 11.5 mm) for ideal beam

- Powered magnets is the baseline
  - failure tolerant serial powering scheme is a necessity

- Tuneable permanent magnets option investigated: it must cover all operational scenarios
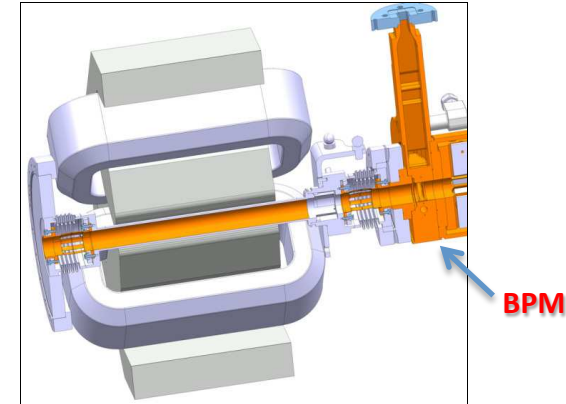
Drive Beam Quadrupole prototype and BPM

Quadrupole specifications			
Total nb. of quads	N_{tot}	~ 42000	-
Inner radius of vacuum chamber	a_0	11.5	mm
Max. integrated gradient	$\hat{G}$	12.2	T
Tunabiliy		See operational scenarios	
Magnet design accuracy rms	$\sigma(Gl)/(Gl)$	1×10^{-3}	-
Resulting magnet design tolerance	$\Delta(Gl)/(Gl)$	$\sqrt{3} \times 10^{-3}$	-
Max. dodecapole component at 11 mm	Int B6 / Int B2	3×10^{-4}	-
Power supply accuracy rms	$\sigma(I)/I$	5×10^{-4}	-

Note that DB correctors will be the girder's articulation points (baseline).

See **E. Adli**'s talk at IWLC 2010

Drive Beam Quadrupoles

Daresbury Lab was asked to look at Permanent Magnet options and also to assess new techniques for building ~50 quads/day

- The CLIC drive beam needs a quadrupole every meter (~42,000)
- The electromagnet option will consume ~400W per magnet
- Want to maintain heat load in tunnel to <150W/m

Why Permanent Magnets?

- No direct power consumption
- No heatload in the tunnel
- Low running costs
- Higher integrated gradient (potentially)

Possible issues: Radiation Damage? Is large tuneability feasible? Is required motion control precision feasible? Sensitivity to material errors & temperature? Sufficient magnet quality?
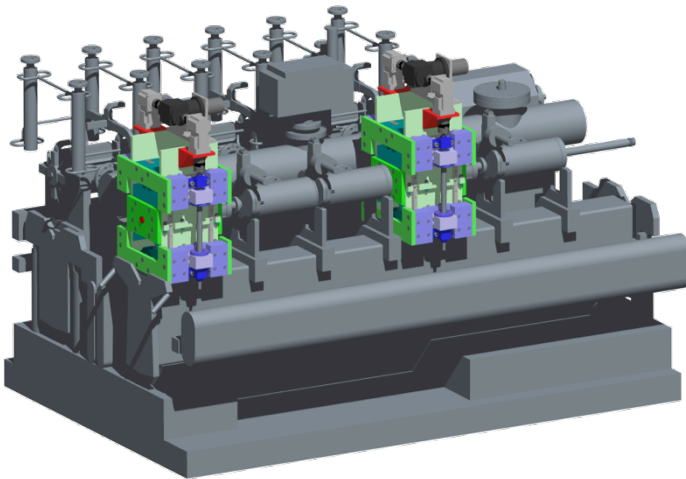
Parameter	Value	
Inscribed radius	14 mm	
PM size	18 x 100 mm	
PM angle	40°	
Magnet length	230 mm	
Maximum stroke	64 mm	
Gradient	81 T/m (max)	8.1 T/m (min)
Integrated gradient	15.0 T (max)	3.6 T (min)
Relative to nominal	123%	30%
Magnetic length	241 mm	
Good gradient region	±7.0 mm	

See **Jim Clarke**'s talk at IWLC 2010
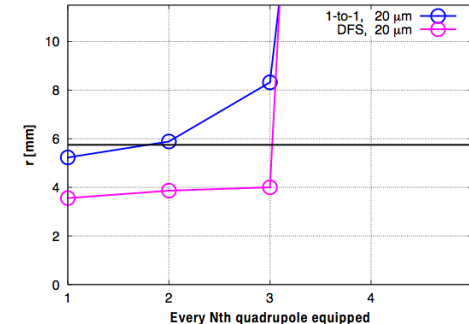
Drive Beam Beam Position Monitors

Beam-based correction performance drive the BPM specifications.
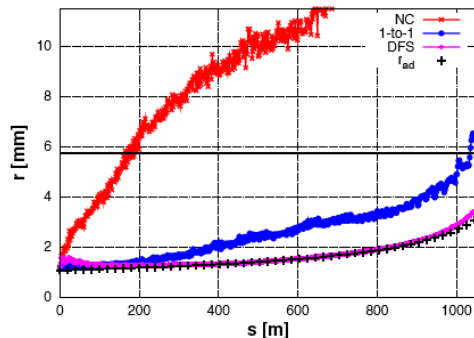Target: negligible envelope growth due to quadrupole kicks.
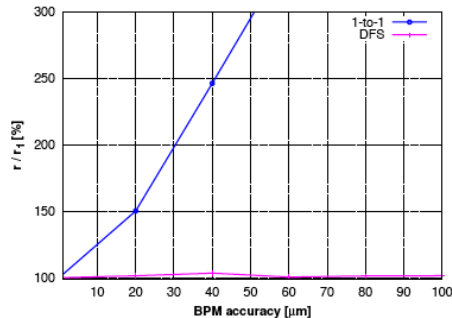
Effect of BPM accuracy
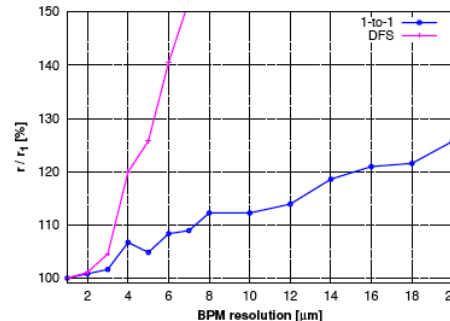
Effect of BPM resolution

Effect of # of BPMs

Results with baseline parameters

Quantity	Symbol	Value	Unit
# of quadrupoles per BPMs	N	$\sim 2/3$	-
Total number of BPMS	N_{tot}	~ 28000	-
Production beam			
BPM accuracy	σ_{acc}	20	μm
BPM resolution	σ_{res}	2	μm
Time resolution	t_{res}	60	ns
Pilot beam			
BPM accuracy	σ_{acc}	20	μm
BPM resolution	σ_{res}	4	μm
Time resolution	t_{res}	60	ns

See **E. Adli**'s talk at IWLC 2010

Main Beam Beam Position Monitors

- The BPM are required for measurement of beam trajectory

- The time resolution was set to less than 50 ns and the spatial one **to 50 nm** for the **MB**. The corresponding accuracy must be better than 5 μm

- A precision of **20 μm** and resolution of about 2 μm are necessary for the **DB**

- The pre-alignment system will be needed for making possible the "first" beams pass through the linac.

- Then, beam-based alignment will be applied using 1:1 correction, Dispersion Free Steering and accelerating cavity alignment

See IWLC 2010, WG8, Instrumentation talks
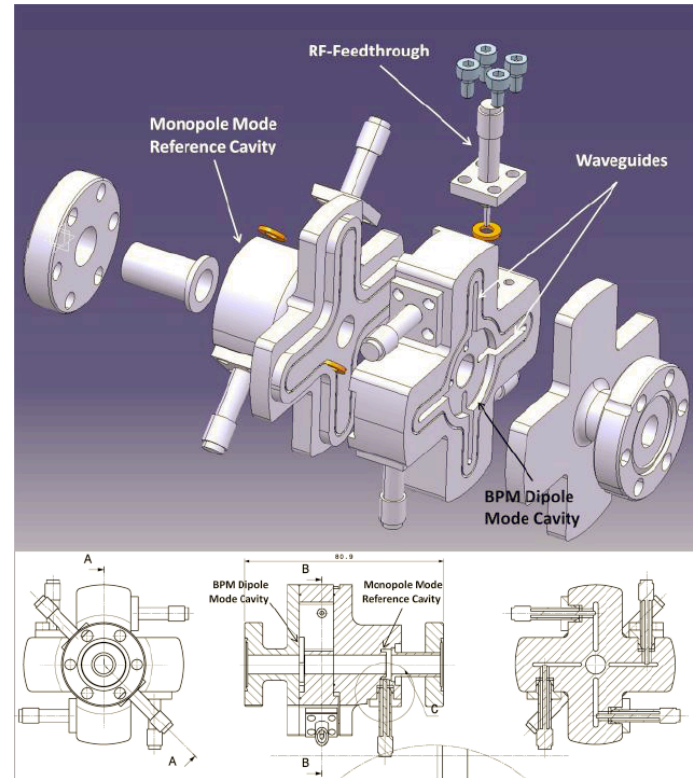
Main Beam Transverse Tolerances

imperfection	with respect to	symbol	value	emitt. growth
BPM offset	wire reference	σ_{BPM}	14 μm	$0.367\,\mathrm{nm}$
BPM resolution		σ_{res}	0.1 μm	$0.04\,\mathrm{nm}$
accelerating structure offset	girder axis	σ_4	10 μm	$0.03\,\mathrm{nm}$
accelerating structure tilt	girder axis	σ_t	140 μradian	$0.38\,\mathrm{nm}$
articulation point offset	wire reference	σ_5	12 μm	$0.1\,\mathrm{nm}$
girder end point	articulation point	σ_6	5 μm	$0.02\,\mathrm{nm}$
wake monitor	structure centre	σ_7	3.5 μm	$0.54\,\mathrm{nm}$
quadrupole roll	longitudinal axis	σ_r	100 μradian	$\approx 0.12\,\mathrm{nm}$

- Selected a good DFS implementation

    - trade-offs are possible

- Multi-bunch wakefield misalignments of $10\,\mu$m lead to $\Delta\epsilon_y \approx 0.13\,\mathrm{nm}$

- Performance of local pre-alignment is acceptable
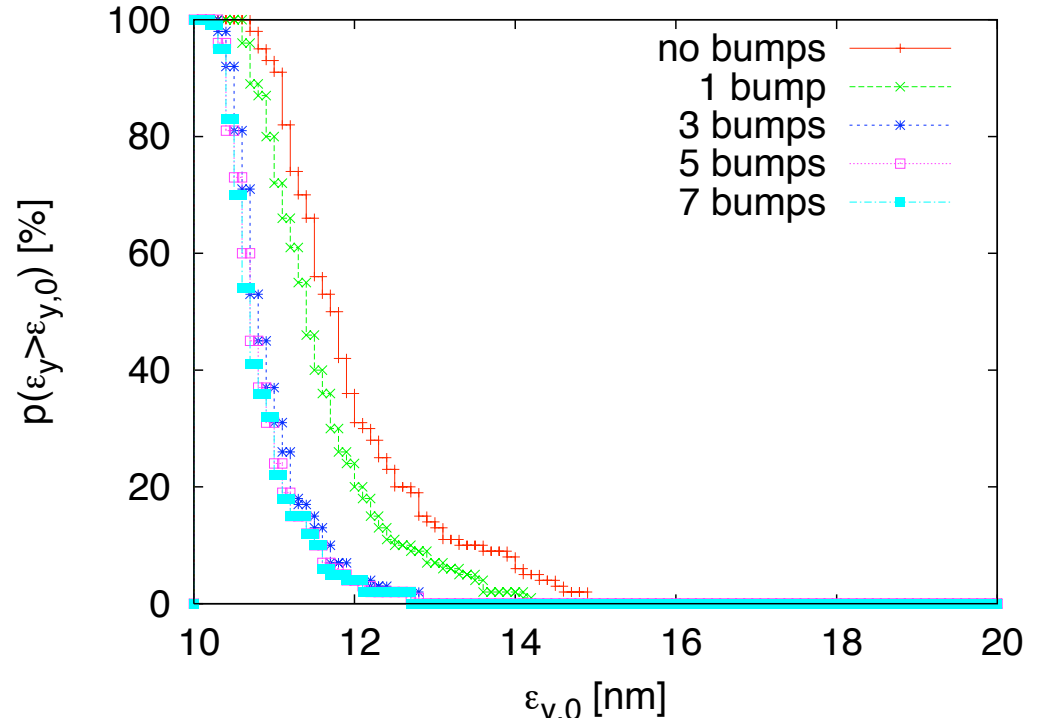
Main to Drive Beam Phase Tolerance

- Integrated simulations have been performed with PLACET and GUINEA-PIG of main linac, BDS and beam-beam

  - system is assumed to be perfectly aligned (to determine BDS bandwidth effect)

  - assuming target emittance at BDS
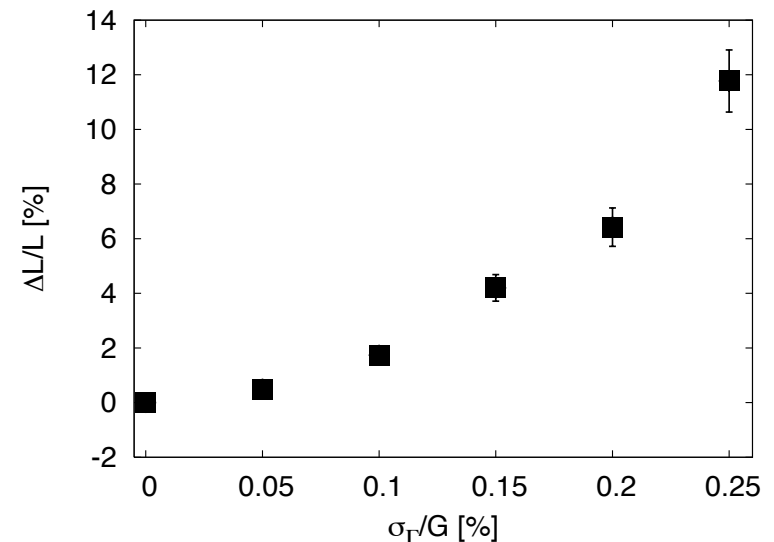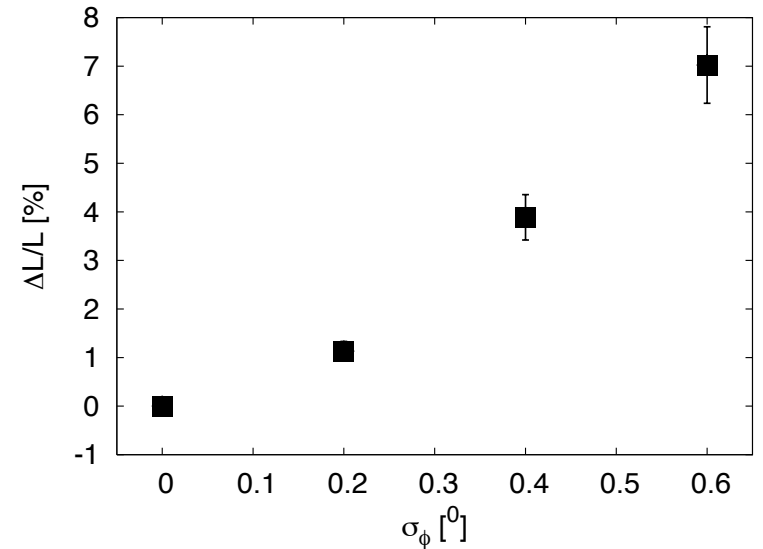
- Resulting luminosity loss is about 2% for

$$\frac{\sigma_G}{G} \approx 1 \times 10^{-3}$$

and

$$\sigma_\phi \approx 0.3°$$

$$\frac{\Delta\mathcal{L}}{\mathcal{L}} \approx 0.01\left[\left(\frac{\sigma_{\phi,coh}}{0.2°}\right)^2 + \left(\frac{\sigma_{\phi,inc}}{0.8°}\right)^2 + \left(\frac{\sigma_{G,coh}}{0.75 \cdot 10^{-3}G}\right)^2 + \left(\frac{\sigma_{G,inc}}{2.2 \cdot 10^{-3}G}\right)^2\right]$$

- Main beam current needs to be stable to ≈ 0.1–0.2%

Cooling System

- A significant part of the RF input power is transferred into heat in the RF structures.

- The cooling system consists of 21 km long linear accelerator circuits with about **20K** temperature difference for each module

- Functions of the cooling system are:
  - Cooling the system
  - Providing micro-meter thermal stability to the accelerator tunnel

    Sustaining the required alignment of 14 μm for ACS within 1σ requires a special development of the cooling system under dynamic heat load conditions

- Ensuring mechanical stability of components, alignment and vacuum systems require evacuating the heat efficiently by specially designed water circuits

- Any vibration induced by coolant flow can result in loss of machine performance

See talk by **G. Riddone**

Estimated Power Dissipation

- Per Accelerating Structure:
  - loaded = 336 W
  - unloaded = 410 W

- Per Module:

Components	Type 0	Type 1	Type 2	Type 3	Type 4
Ac. structures [W]	3285	2464	1642	821	
PETS [W]	352	264	176	88	
DB quadrupoles [W]	342	342	342	342	342
MB quadrupole [W]		890	1780	2600	3831
Loads [W]	2861	2146	1430	715	
WGs [W]	45	34	23	11	
Total per module [W]	6885	6139	5393	4578	4173

See talk by **G. Riddone**

Vacuum: Requirements from Beam Dynamics

Proceedings of IPAC10 , J.-B. Jeanneret, G. Rumolo, D. Schulte
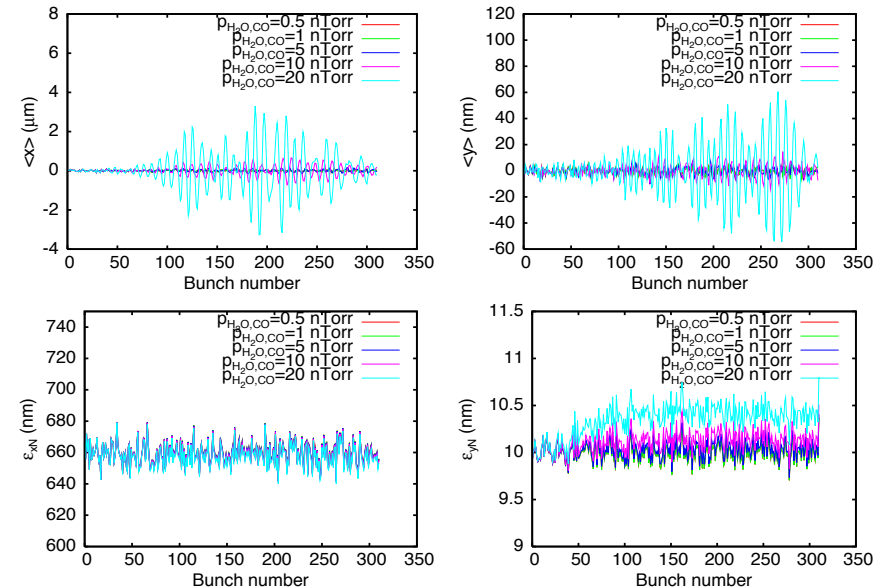
Simulations with the FASTION Code

New fast ion instability simulations show that the influence of field ionization for a threshold electric field value between 18 and 30 GV/m, which covers the common gas species H2, CO, N2 and H20, makes the **beam unstable for partial pressures above 5 nTorr**.

A dynamic pressure of **1 nTorr** must be specified in order to ensure beam stability. In the future, we plan to simulate the fast ion instability for a more realistic composition of the residual gas

See talk by **W. Wuensch**

Concluding…

- The layout of the two-beam acceleration modules has been presented, and each subsystem has been introduced

- Answers to how to cope with the presented requirements and technical issues will be given in the following talks…

- I wish to thank all the people that have helped me during the preparation of this talk.