REVIEW OF THE BASELINE RF MODULE DESIGN AND HIGH REPETITION RATE OPTIONS

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ACCELERATING STRUCTURE OPTIMIZATION

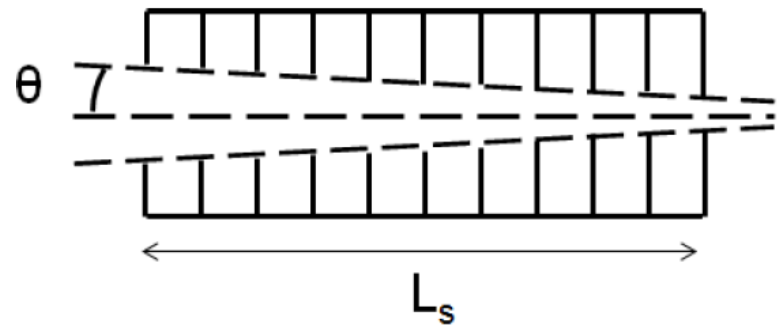
A **numerical tool** able to calculate the main **structure parameters** (effective shunt impedance, modified Poynting vector, E_{acc} field profile) **with an arbitrary cell-by-cell iris modulation along the structure itself has been developed** (*M. Diomede et al., j.nima.2018.01.032, (2018)*). **A linear tapering of the cell irises** has been adopted.

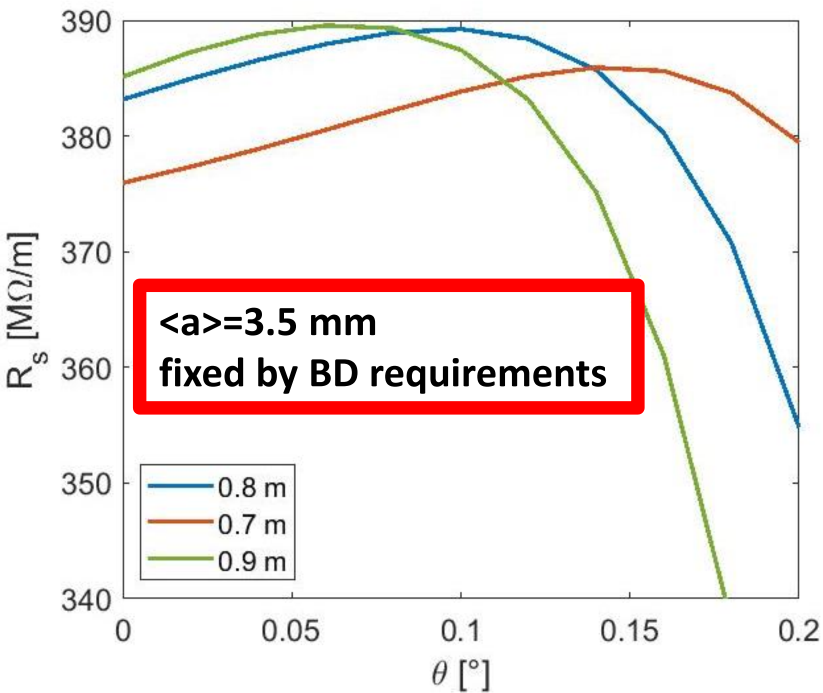
Accelerating Voltage : V_a

Klystron output power : P_K

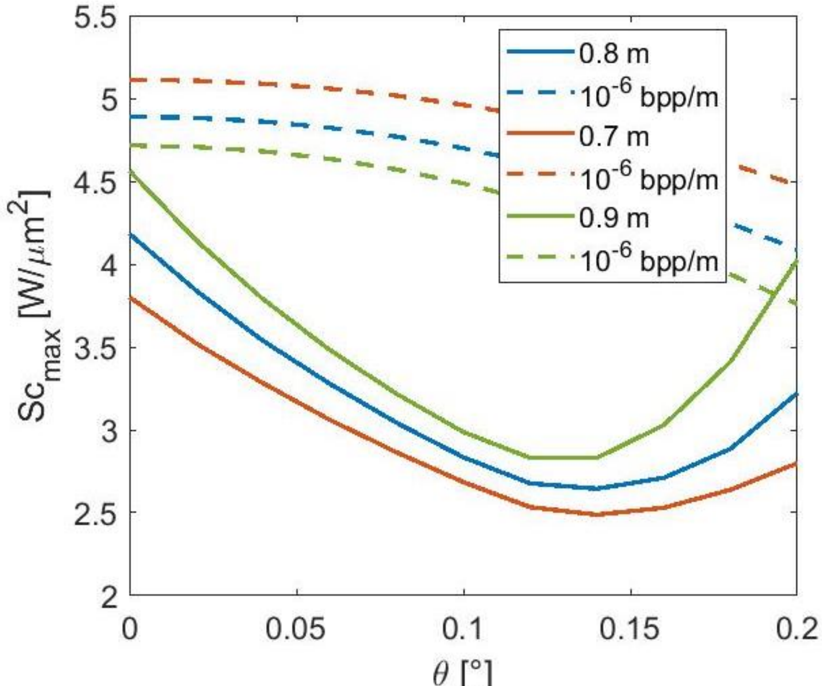
$$\text{Effective shunt impedance}: \quad R_s = \frac{V_a^2}{P_K(t=0)L_s}\left[\frac{\Omega}{m}\right]$$

Structure with linear iris tapering





E_{acc}=65 MV/m



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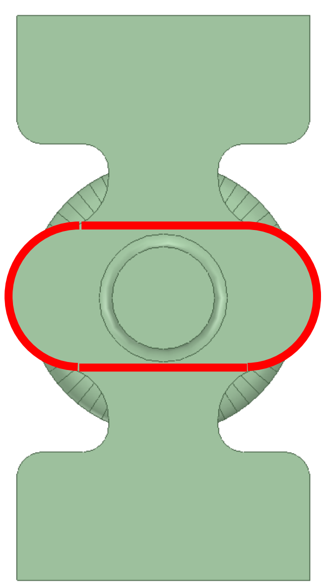
COUPLER DESIGN

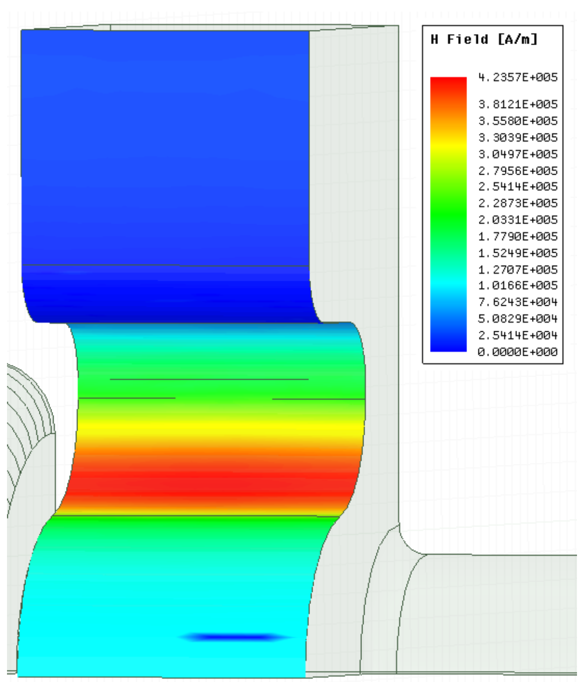
⇒ We considered a **z-type coupler** because of its compactness with respect to the waveguide and mode launcher ones.

⇒ **Dual feed** allows to completely avoid the dipole magnetic field component.

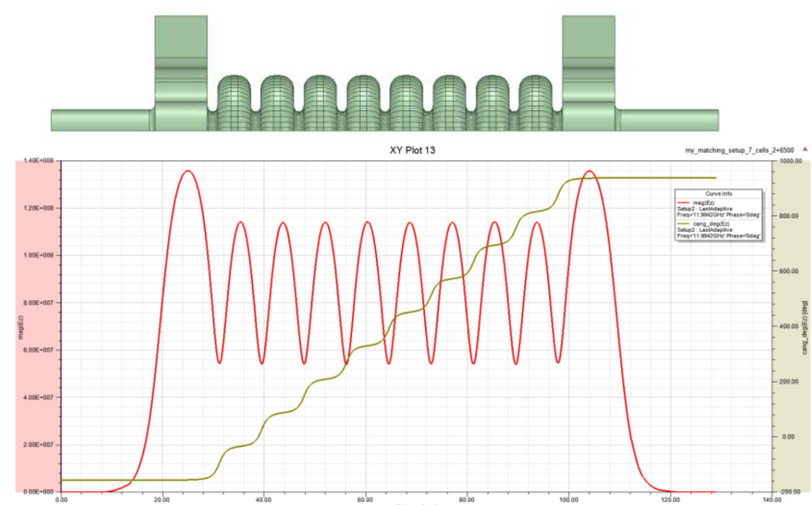
⇒ **Racetrack geometry** has been implemented in order **to compensate the residual quadrupole field components.**

⇒ The calculated **pulsed heating** on the input coupler is **<15 °C** (in the 65 MV/m case), the obtained **reflection coefficient** is **<−30 dB**.



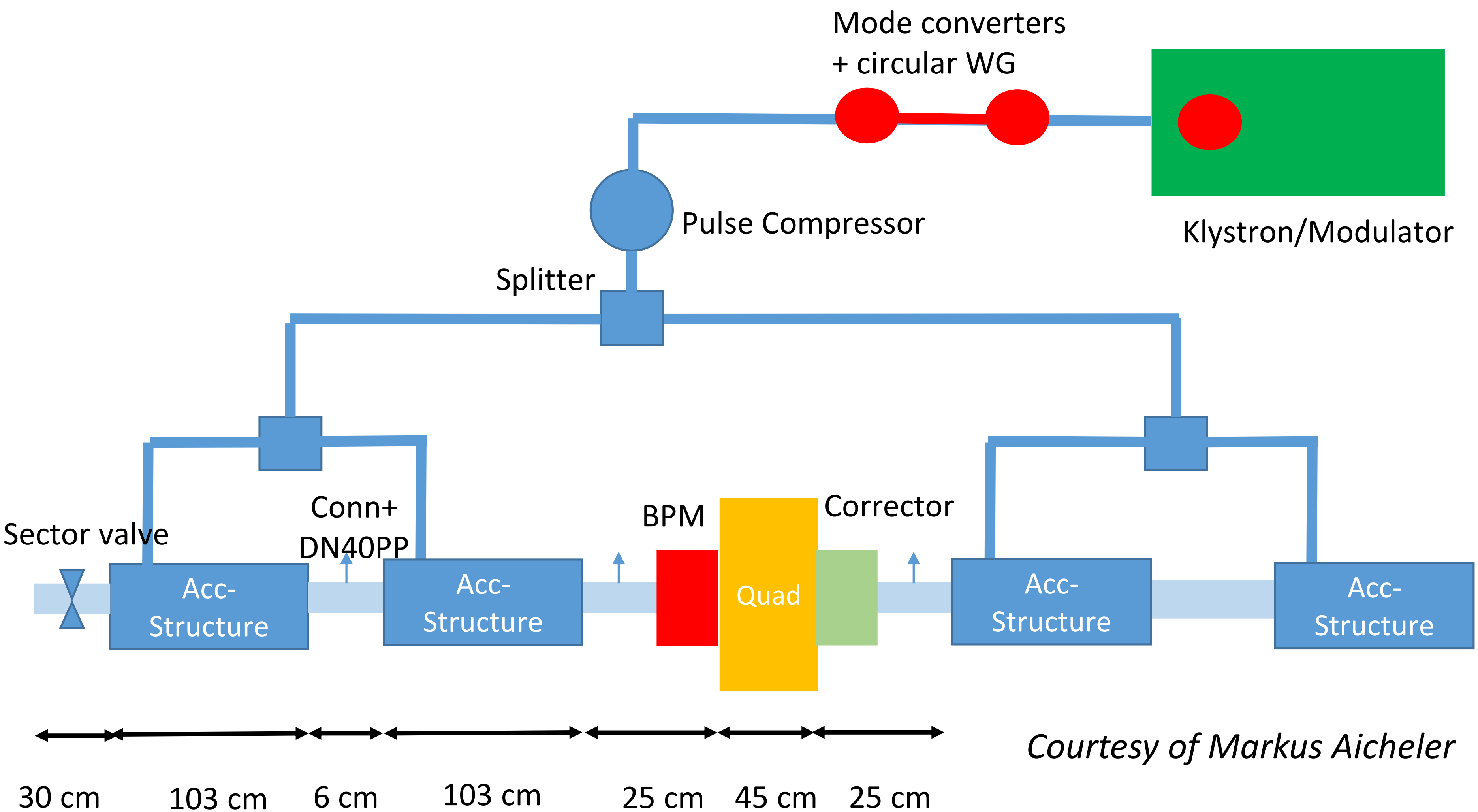


7 cells model



CONCEPTUAL LAYOUT OF THE ACCELERATING MODULE

The **RF module** is then made up of **4 TW structures** fed by **1 klystron** with **1 SLED**.



Courtesy of Markus Aicheler

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ACCELERATING STRUCTURE AND MODULE: PARAMETERS

Parameter	Value
Frequency [GHz]	11.9942
RF pulse [μs]	1.5
Phase advance per cell [rad]	$2\pi/3$
Shunt impedance R [MΩ/m]	90-131
Effective shunt Imp. R_s [MΩ/m]	387
Group velocity v_g [%]	4.7-1.0
P_{out}/P_{in}	0.215
Filling time [ns]	**144**
Number of cells per structure	108
Unloaded SLED Q-factor Q_0	180000
External SLED Q-factor Q_E	23000
# structures per module N_m	**4**
Module active length L_{mod} [m]	3.6

	Rep. rate [Hz]	
	100	1000
Average gradient <G> [MV/m]	**65**	**22.7**
Klystron power per module P_K [MW]	**39**	**4.8**
Av. diss. power 100 Hz [kW]	**1.1**	**1.34**
Peak input power per structure [MW]	68	8.3
Av. Input power per structure [MW]	44	5.4
Module energy gain [MeV]	**234**	**81.7**

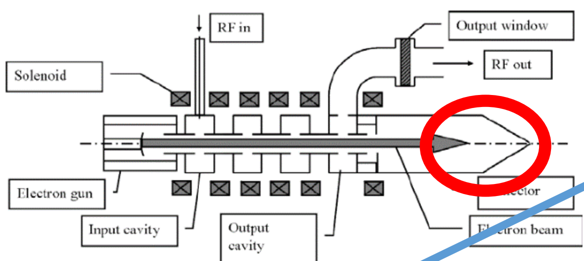
Parameter	Value
Average iris radius <a>	**3.5**
Iris radius input-output [mm]	**4.3-2.7**
Structure length L_s [m]	**0.9**
Accelerating cell length [mm]	8.332

HIGH REPETITION RATE OPERATION

The high repetition rate operation is limited by two effects:

The **average dissipate power in the structure**: is someting manageable.

The **main limitation** for the rep rate increasing comes from the ***power released*** on the ***tube collector*** P_{coll} which can ***not exceed*** a ***limit value*** corresponding to the **nominal working point** (with some margin).



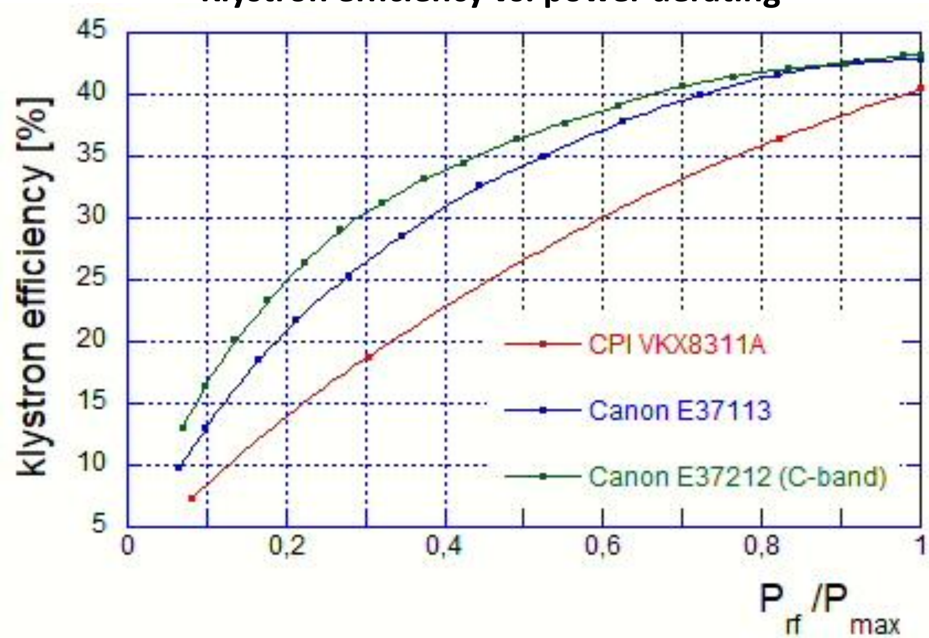
$$P_{coll} \simeq \frac{P_{RF_{sat}}}{\eta}(\tau_{pulse} + \tau_{trans}) f_{rep}$$

The amount of rep rate increase obtained by **reducing the pulse duration** depends very much on the actual value of the **dead time** $\boldsymbol{\tau_{trans}}$, which is a **characteristics of the modulator**.

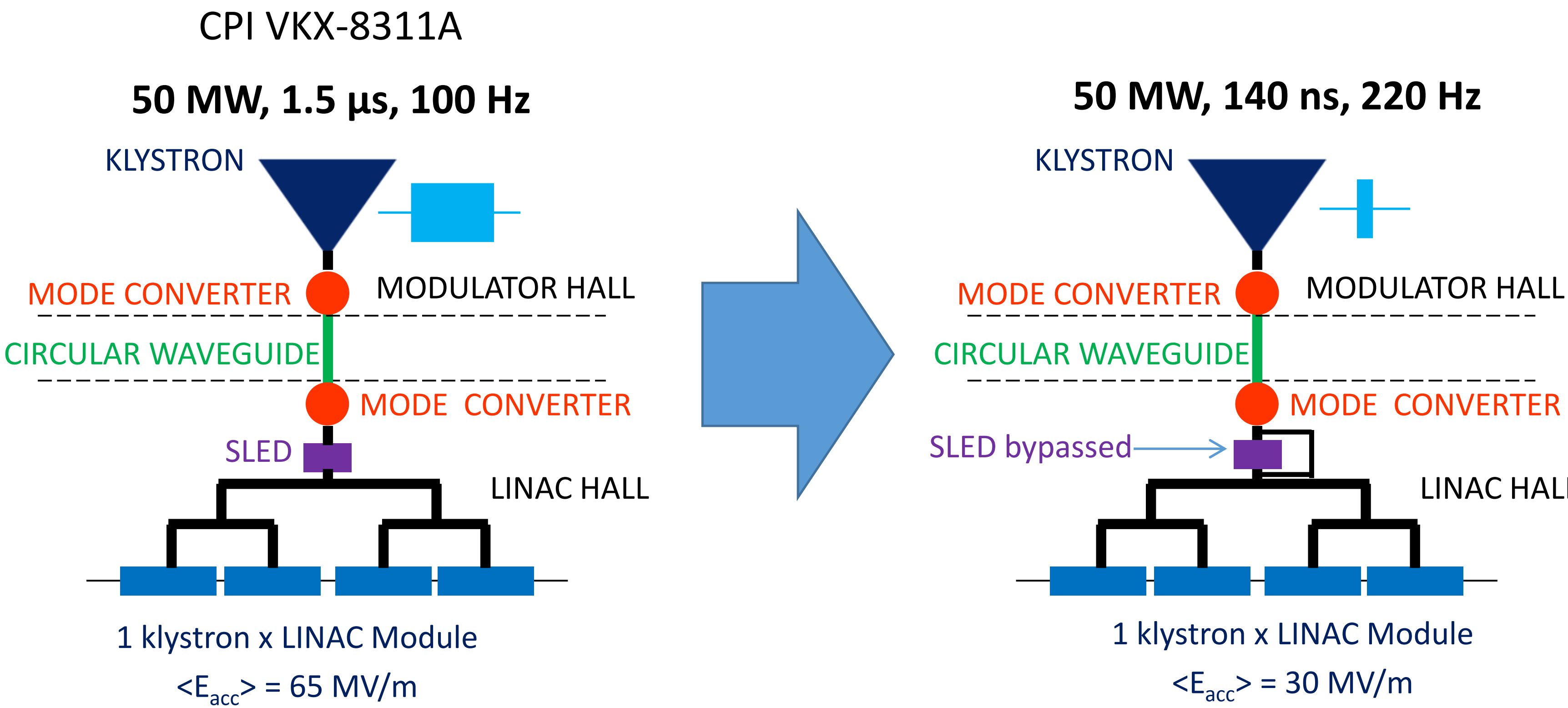
The klystron operational ***rep rate*** can be ***increased*** at expenses of the ***saturated RF power*** (by decreasing the tube HV) and/or the ***pulse duration***

The amount of rep rate increase obtainable by **reducing the HV** and the RF saturation power $P_{RF_{sat}}$ is limited by the **tube efficiency decrease**.

Klystron efficiency vs. power derating



HIGH REPETITION RATE 1st SCENARIO: PULSE SHORTENING WITH HIGH PEAK POWER KLYSTRONS



- **Accelerating gradient and Linac energy reduced by a factor 2.2 @ 220 Hz rep rate**;
- **The SLED has to be bypassed**;
- Klystron operated always at its nominal working point (good!);
- **Max rep rate very much dependent on modulator dead time τ_{trans}**

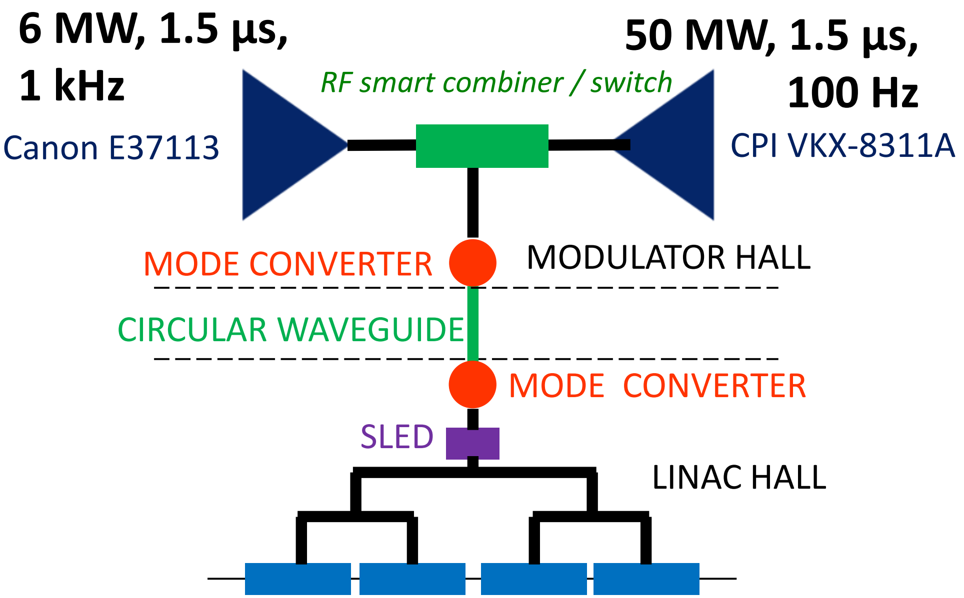
HIGH REPETITION RATE 2nd SCENARIO: LOW POWER HIGH REP. RATE KLYSTRONS

Canon E37113 klystrons

Scandinova solid state modulators

Parameters	Specifications	units
	E37113	
RF Frequency	11.9942	GHz
Peak RF power	6	MW
RF pulse length	5	μs
Pulse repetition rate	400	Hz
Klystron voltage	150	kV
Micro perveance	1.5	

6 MW, 1.5 μs, 1 kHz operation probably possible



$\langle E_{acc} \rangle$ = 22.7 MV/m @ 1 kHz

2 klystrons x LINAC Module

$\langle E_{acc} \rangle$ = 65 MV/m @ 100 Hz

- **1 kHz rep rate capability, with linac energy up to ≈ 35% of the max value**;
- Switching or combining 2 sources would preserve **high gradient at low rep rate**;
- If source combination is possible, **gradients > 30 MV/m available at rep rates ≤ 250 Hz**;
- **CPI** will probably announce a **new tube** capable of delivering **10 MW, 1.5 μs, 1 kHz** (gradient of **30 MV/m**)

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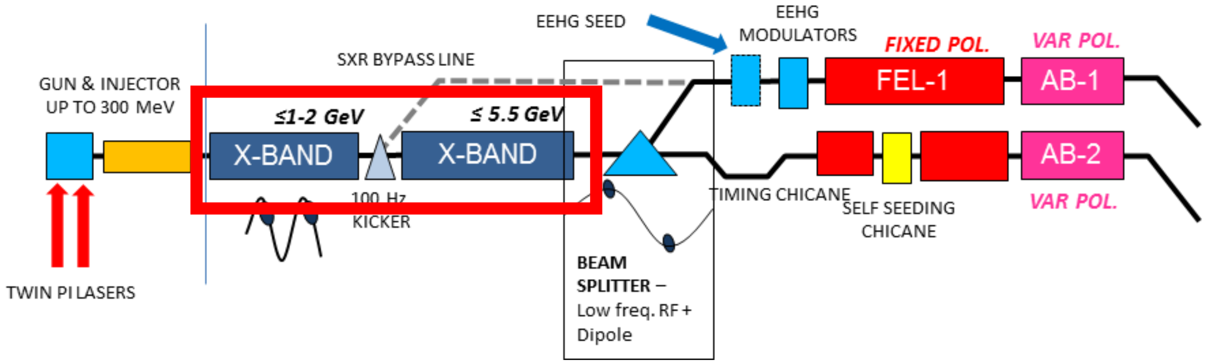
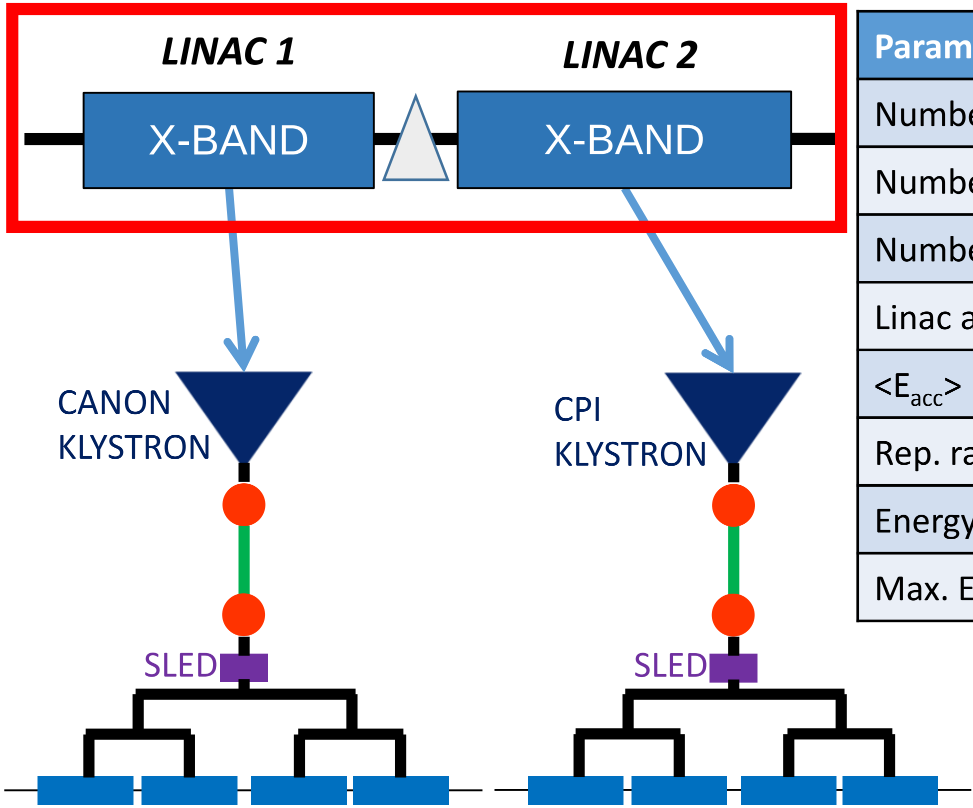
HIGH REP. RATE LINAC: 1st OPTION





$<E_{acc}>$ = 22.7 MV/m @ 1 kHz $<E_{acc}>$ = 65 MV/m @ 100 Hz

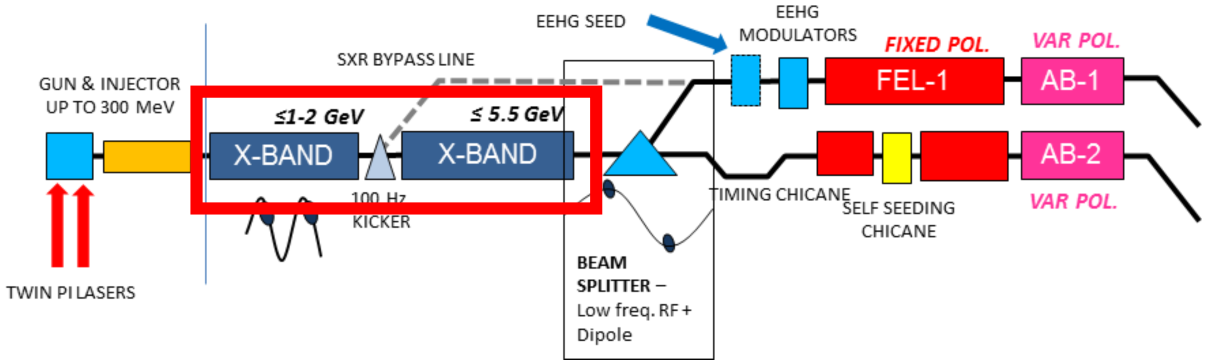
Parameter	LINAC 1	LINAC 2	TOTAL
Number of structures	92	60	152
Number of modules	23	15	38
Number of klystrons	23 (Canon)	15 (CPI)	38
Linac active length [m]	83	54	137
$<E_{acc}>$ per struct. [MV/m]	22.7	65	-
Rep. rate [Hz]	1000	100	-
Energy gain per module [MeV]	81.7	234	-
Max. Energy gain [MeV]	1880	3510	5390

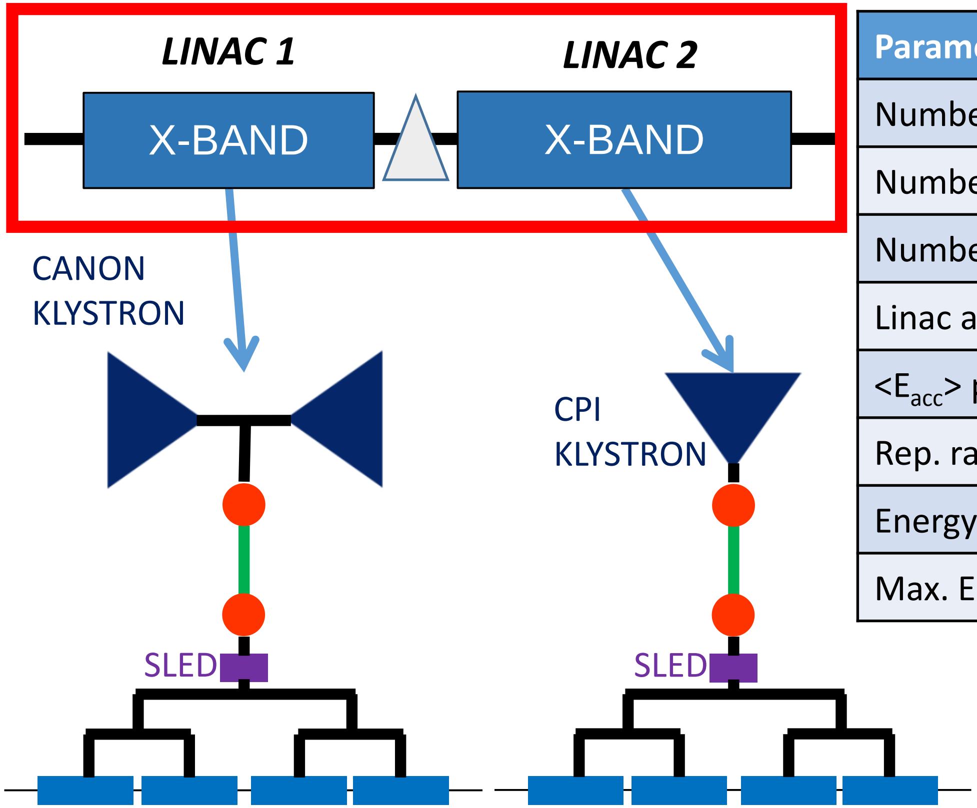
⇒ **SXR@ 1 kHz**

⇒ **HXR@ 100 Hz**

⇒ **SXR@ 900 Hz and HXR@ 100 Hz can run in parallel**

HIGH REP. RATE LINAC: 2nd OPTION





$<E_{acc}>$ = 32.1 MV/m @ 1 kHz $<E_{acc}>$ = 65 MV/m @ 100 Hz

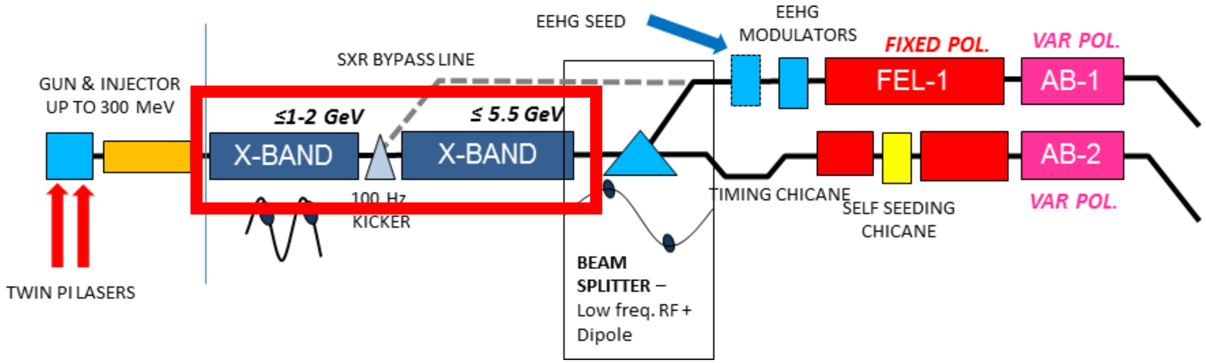
Parameter	LINAC 1	LINAC 2	TOTAL
Number of structures	64	60	124
Number of modules	16	15	31
Number of klystrons	32 (Canon)	15 (CPI)	47
Linac active length [m]	58	54	112
$<E_{acc}>$ per struct. [MV/m]	32.1	65	-
Rep. rate [Hz]	1000	100	-
Energy gain per module [MeV]	115.6	234	-
Max. Energy gain [MeV]	1850	3510	5360

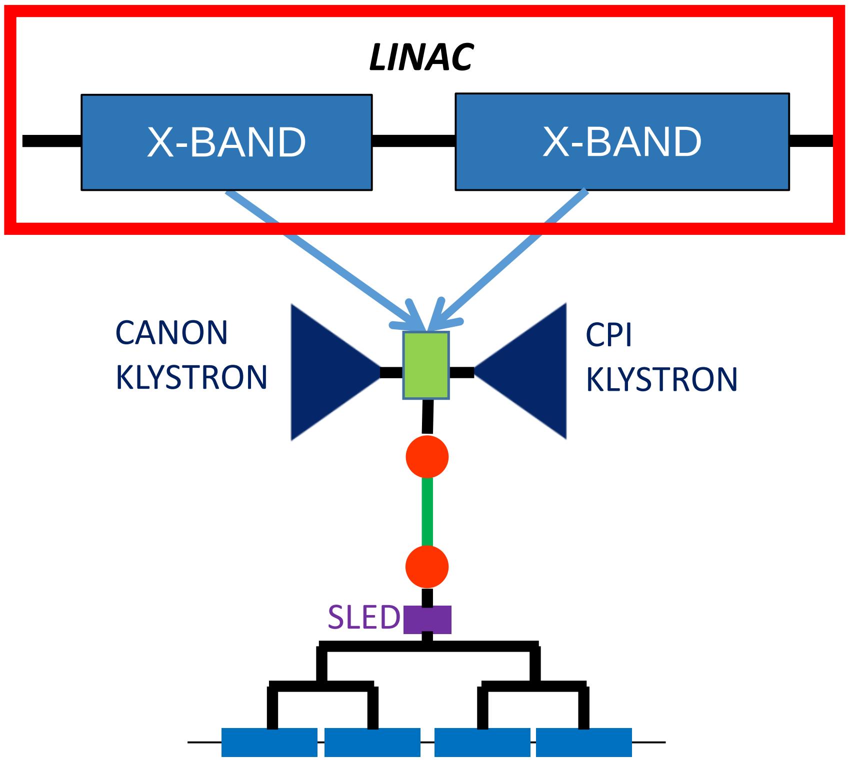
⇒ **SXR@ 1 kHz**

⇒ **HXR@ 100 Hz**

⇒ **SXR@ 900 Hz and HXR@ 100 Hz can run in parallel**

HIGH REP. RATE LINAC: 3rd OPTION





$\langle E_{acc} \rangle$ = 22.7 MV/m @ 1 kHz

$\langle E_{acc} \rangle$ = 65 MV/m @ 100 Hz

Parameter	LINAC
Number of structures	**92**
Number of modules	**23**
Number of klystrons	**23 (Canon) + 23 (CPI)**
Linac active length [m]	**83**
$\langle E_{acc} \rangle$ per struct. [MV/m]	**22.7 (@1 kHz), 65 (@ 100 Hz)**
Rep. rate [Hz]	**100-1000**
Energy gain per module [MeV]	**81.7 (@1 kHz), 234 (@ 100 Hz)**
Max. Energy gain [MeV]	**1880 (@1 kHz), 5380 (@ 100 Hz)**

⇒ **SXR@ 1 kHz**

⇒ **HXR@ 100 Hz**

⇒ **SXR and HXR CANNOT run in parallel!**

CONCLUSIONS

1) **Accelerating structure electromagnetic design completed**

2) **Basic module with 4 structures fed in parallel**. NB The Compact Light module is now the same of the **EuPRAXIA@SPARC_LAB** module (originally shorter because of the smaller iris radius).

3) **Three different options for the linac have been proposed**. They allow SXR operation @ 1 kHz and HXR operation at 100 Hz

4) **Next steps**:

   - refinement of input/output coupler design
   - cooling system design
   - mechanical drawing of the accelerating structure

...THANK YOU FOR YOUR ATTENTION!

Thank you also to Dr. Toshiro Anno (Canon) and CPI Company for data/information and useful suggestions on Klystron high rep. Rate operation