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The CompactLight Design Study Project

Gerardo D'Auria, Elettra – Sincrotrone Trieste,

on behalf of the CompactLight Collaboration (XLS)

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The CompactLight Collaboration

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CompactLight (XLS) is an initiative among several International Laboratories aimed at promoting the construction of the next generation FEL based photon sources.

	Organisation Name	Country
1	Elettra – Sincrotrone Trieste S.C.p.A.	Italy
2	CERN - European Organization for Nuclear Research	Intern.
3	Science and Tech. Facility Council – Daresbury Lab.	UK
4	Shanghai Institute of Applied Physics	China
5	Institute of Accelerating Systems and Applications	Greece
6	Uppsala Universitet	Sweden
7	Melbourne University	Australia
8	Australian Nuclear Science and Tecnology Org.	Australia
9	Ankara Univ. Institute of Accel. Techn.	Turkey
10	Lancaster Univ.	UK
11	VDL Enabling Technology Group Eindhoven	NL
12	Technische Universiteit Eindhoven	NL
13	Istituto Nazionale di Fisica Nucleare	Italy
14	Kyma S.r.l.	Italy
15	Rome Univ. "La Sapienza"	Italy
16	ENEA	Italy
17	ALBA Lab. de Luz Sincrotron	Spain
18	CNRS Centre Nat. de la Rech. Scient.	France
19	Karlsruher Instritut für Technologie	Germany
20	Paul Scherrer Institute	CH
21	CSIC Valencia Univ.	Spain
22	Helsinki Univ. Institute of Physics	Finland
23	ARCLN Amsterdam	NL
24	Strathclyde Univ.	UK

http://CompactLight.eu

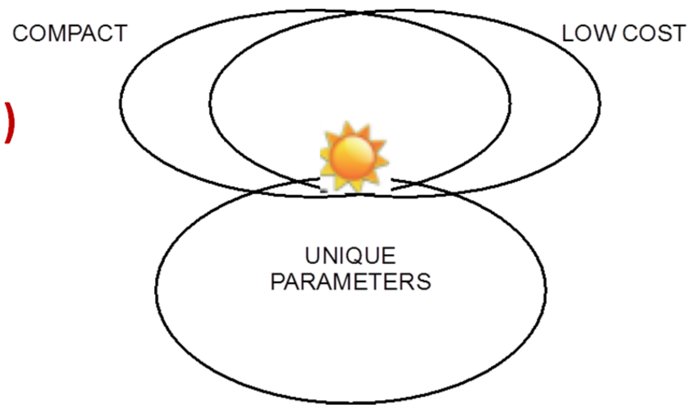
- **CompactLight is an EU Design Study (RIA)**
- **Starting date 01-01-2018**
- **Duration 36 months**
- **Total cost of the project 3.5 M€**
- **EU contribution: 3 M€**
- **24 participating organisations within 13 countries including CERN + 5 associated partners.**
- **7 Work Packages**

XLS Objectives

Our aim is to facilitate the widespread development of X-ray FEL facilities across Europe and beyond, by making them more affordable to construct and operate through an optimum combination of emerging and innovative accelerator technologies.

Based on FEL Scientific Requirements collected from the Scientific Community, we plan to design a hard X-ray facility using the latest concepts for:

- ✓ **High brightness electron photoinjectors**
- ✓ **Very high gradient accelerating structures (X-band)**
- ✓ **Novel short period undulators**



Users requirements

ESSENTIALS:

- Photon energy range at the fundamental: 0.25 – 16.0 keV
- Variable, selectable polarization
- Repetition rate 100 Hz (higher, very welcome!)
- 2-colours operation with timing separation +/- 100fs and colour separation 20% in SXR and 10% in HXR
- Wavelength tuning primarily by undulator scanning with several discrete beam energies
- Pulse duration 1- 50 fs
- Even pulse spacing and <10 fs synchronisation between FEL pulse and external laser
- Competitive pulse energy

DESIDERABLES:

- Stability
- Seeding at all wavelengths
- Repetition rate 1kHz
- Simultaneous HXR/SXR operation
- Peak brightness 10^{33} ph/s/mm mrad^2/0.1%bw at 16keV

FEL Parameters

Preliminary FEL Parameters based on user's requirements

Parameter	Unit	Soft x-ray FEL	Hard x-ray FEL
Photon energy	KeV	0.25 - 2.0	2.0 - 16.0
Wavelength	nm	5.0 - 0.6	0.6 - 0.08
Repetition rate	Hz	100 to 1000*	100
Pulse duration	fs	0.1 - 50	
Pulse energy	mJ	< 0.3	
Polarization		Variable - Selectable	
Two-pulse delay	fs	± 100	
Two-colour separation	%	20	10
Synchronization	fs	< 10	

*A repetition rate of 1000 Hz would be a unique and desirable feature of our design! We recognise that this is a very challenging target that we may have to reduce during the study.

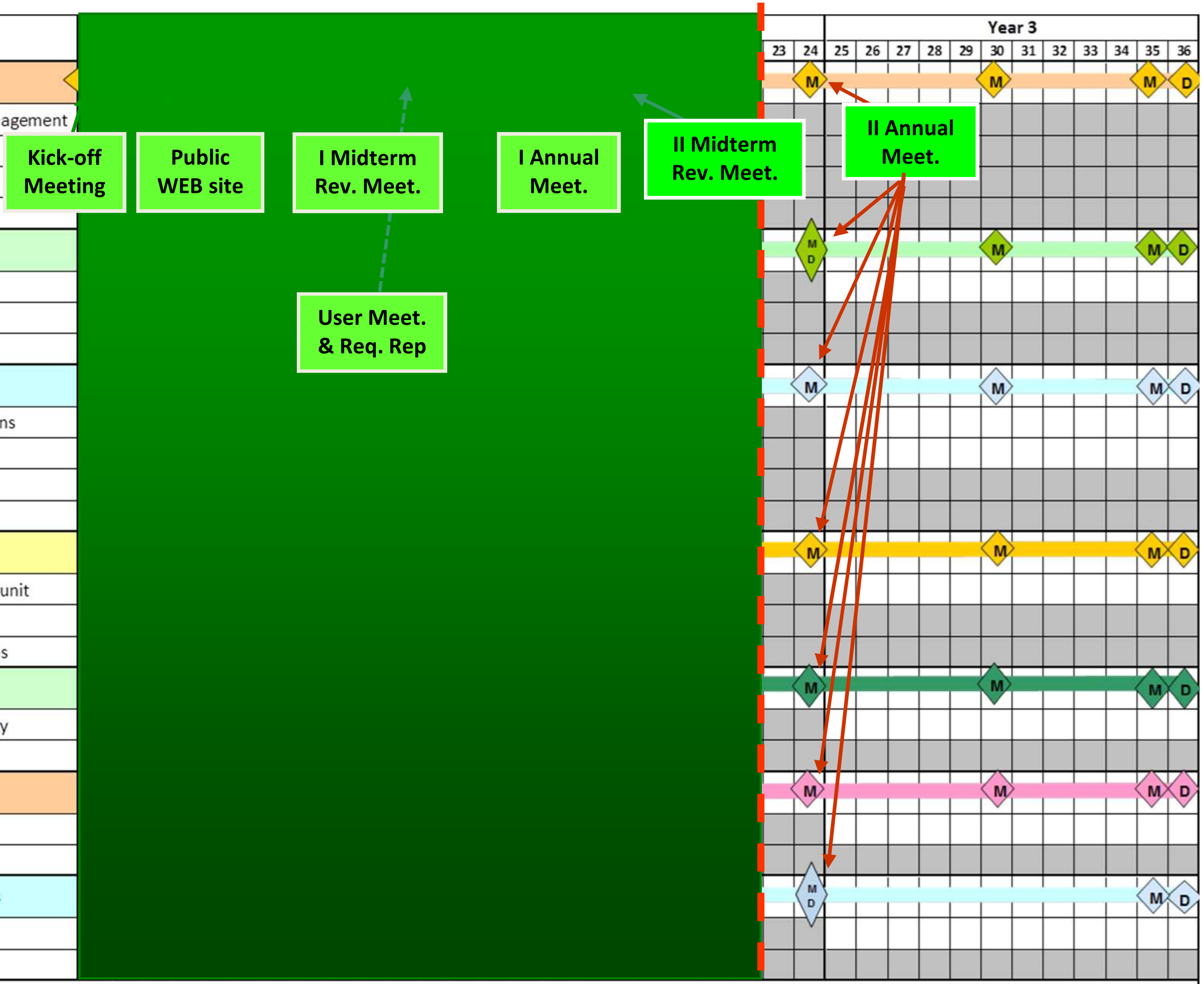
XLS Work Packages

Work Package		Lead Participant	Person Months	Start Month	End month
WP1	Project Management and Technical Coordination	Elettra – Sincrotrone Trieste	32	1	36
WP2	FEL Science Requirements and Facility Design	STFC	68	2	36
WP3	Gun and Injector	INFN	76	2	36
WP4	RF systems	CERN	78	2	36
WP5	Undulators and Light production	ENEA	81	2	36
WP6	Beam dynamics and Start to End Modelling	UA-IAT	78	2	36
WP7	Global Integration with New Research Infrastructures	Elettra - ST	27	6	36
		Total Person Months	440		

XLS Objectives

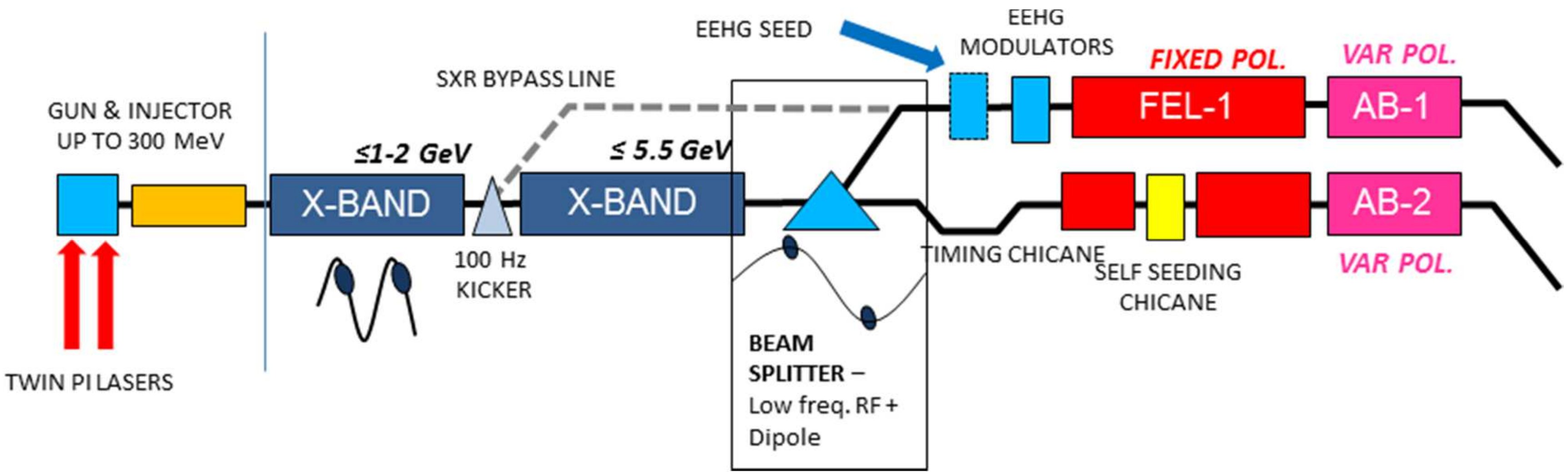
WP Task	Description
1	**Project Management and Technical Coordination**
1.1	General governance of CompactLight and scientific management
1.2	Monitoring and reporting, partners coordination
1.3	Administrative and financial coordination
1.4	Dissemination of information
2	**FEL Science Requirements and Facility Design**
2.1	User requests and FEL performance
2.2	FEL layout, accelerator and undulator requirements
2.3	CompactLight CDR
3	**Gun and Injector**
3.1	Evaluation of e-gun and injector technologies and options
3.2	Bunch compressors and phase space linearization
3.3	Beam diagnostics and manipulation
3.4	E-gun and injector design
4	**RF Systems**
4.1	Parametrized of performance and cost model of the RF unit
4.2	Design report of optimized rf unit
4.3	Accelerating structure design and fabrication procedures
5	**Undulators and Light production**
5,1	Near and medium term (4-5 years) undulator technology
5,2	Design report of the baseline undulator for the facility
6	**Beam Dynamics and Start to End modeling**
6,1	Tools for evaluating the facility performance
6,2	Start to end simulation of the facility
7	**Global integration with new Research Infrastructures**
7,1	Mid term reports for integration and services analysis
7,2	Final report integration, services and cost analysis

D = Deliverable
M = Milestone



CompactLight Gant chart

Facility layout & operating modes



Operating modes:

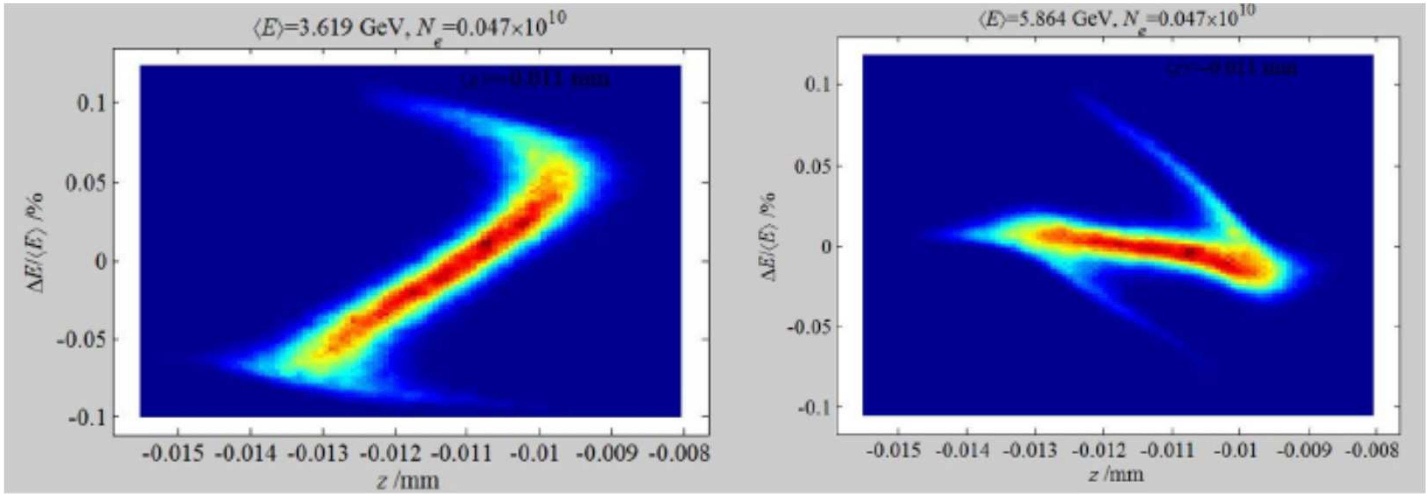
1. FEL-1/FEL-2 independent double pulses to one experiment HXR 100Hz
2. FEL-1/FEL-2 independent single pulses to two experiments HXR 100Hz
3. FEL-1/FEL-2 independent double pulses to one experiment SXR 1kHz
4. FEL-1/FEL-2 independent single pulses to two experiments SXR 1kHz
5. FEL-1 SASE/SEEDED SXR 100Hz + FEL-2 SASE/SELF SEEDED HXR 100Hz

D. Dunning , N. Thompson

Electron beam parameters

Parameter	Value
Max energy	5.5 GeV @100 Hz
Peak current	5 kA
Normalised emittance	0.2 mm.mrad
Bunch charge	< 100 pC
RMS slice energy spread	10^{-4}
Max photon energy	16 keV
FEL tuning range at fixed energy	×2
Peak spectral brightness @16 keV	10^{33} ph/s/mm²/mrad²/0.1%bw

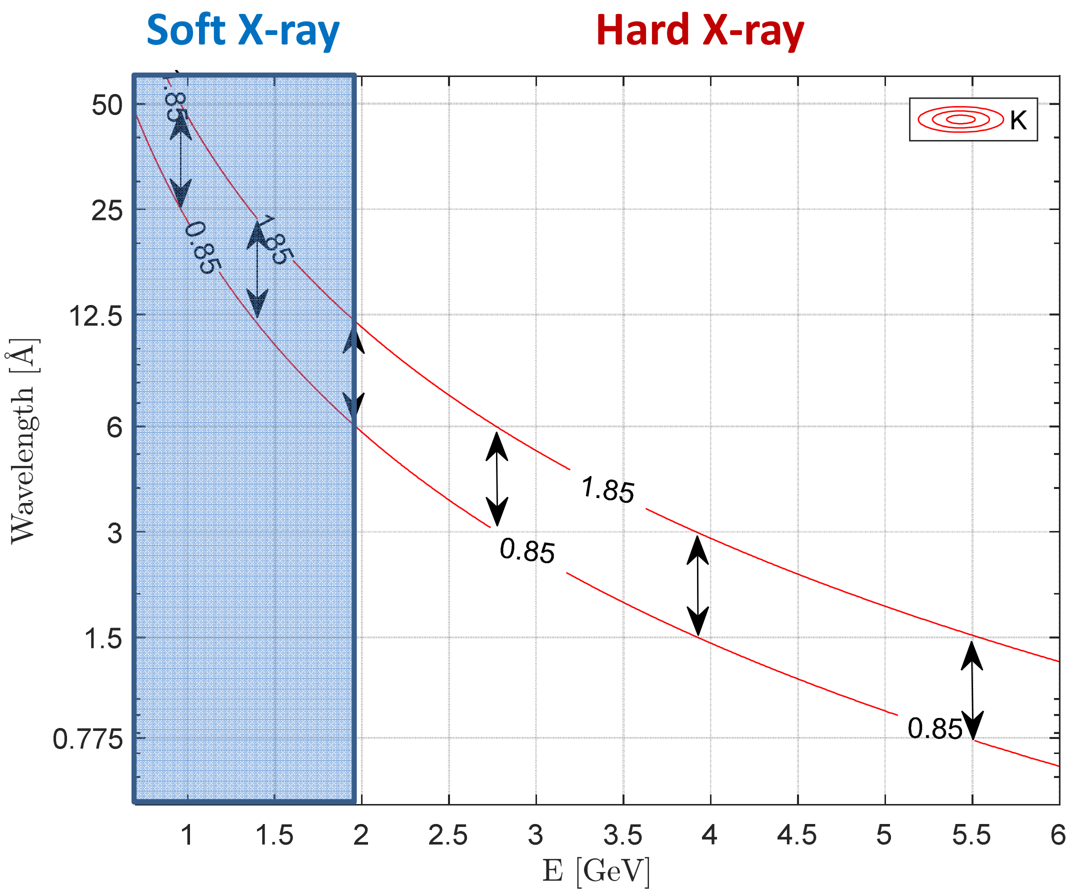
Main Electron Beam Parameters



Longitudinal phase space from 1-D tracking at the exit of the linac for SXR FEL (left) and at the exit of the linac for HXR FEL (right)

S. Di Mitri

Undulator parameters



Both undulator lines have identical parameters, so K is tuneable to provide a factor of 2 wavelength tuning for both Soft X-ray and Hard X-ray

$\lambda_u \approx 13mm$
$K_u \approx 0.85\text{-}1.85$

- **Soft X-ray**
  $E_{beam} \approx 1.0/1.4/1.95GeV$
  (~3 discrete working points @increased rep.rate, TBC)

- **Hard X-ray**
  $E_{beam} \approx 2.75/3.9/5.5GeV$
  (~3 discrete working points @100Hz)

D. Dunning

Genesis Time Dependent simulations @ 16keV (3mm gap)
Summary of results

	CPMU	Delta	Hybrid	SCU
Saturation Power (mean over pulse) (GW)	9.1	8.9	7.6	9.8
Saturation Length (m)	24.5	26.5	29.1	15.6
Saturation Pulse Energy (μJ)	49	48	29	54
FWHM Bandwidth	9.87e-4	9.75e-4	9.96e-4	1.16e-3
Peak Brightness (mean over pulse) #ph/s/mm^2/mrad^2/0.1%bw	2.39e33	2.37e33	1.98e33	2.18e33

Accelerating gradients

European XFEL (Germany)	24 MV/m	Superconducting L-band
Swiss FEL (Switzerland)	28 MV/m	Normal-conducting C-band
SACLA (Japan)	35 MV/m	Normal-conducting C-band

Examples of Linac gradients for most recent X-ray FELs

Parameter	Value
Length L	0.75m
Phase advance per cell φ	120°
First iris aperture a1/λ	0.15
Last iris aperture a2/λ	0.1
First iris thickness d1	0.9mm
Last iris thickness d2	1.7mm
Fill time τ	150ns
Operational gradient G	65MV/m
Input power Pin	41.8MW

Preliminary parameters of an optimized RF structure (X-band)

Preliminary parameters of the X-band RF unit, compared with the C-band SwissFEL technology.

	unit	XLS X-band	SwissFEL C-band
Structures per RF unit		10	4
Klystrons per RF unit		2	1
Structure length	m	0.75	1.98
Allowed gradient	MV/m	80+	
Operating gradient	MV/m	65	27.5
Energy gain per RF unit	MV	488	203
Klystron nominal power	MW	50	50
Power in operation	MW	45	40
Klystron pulse length	µs	1.5	3
RF energy/pulse/GeV	J	277	591

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CLIC X-band accelerating structure

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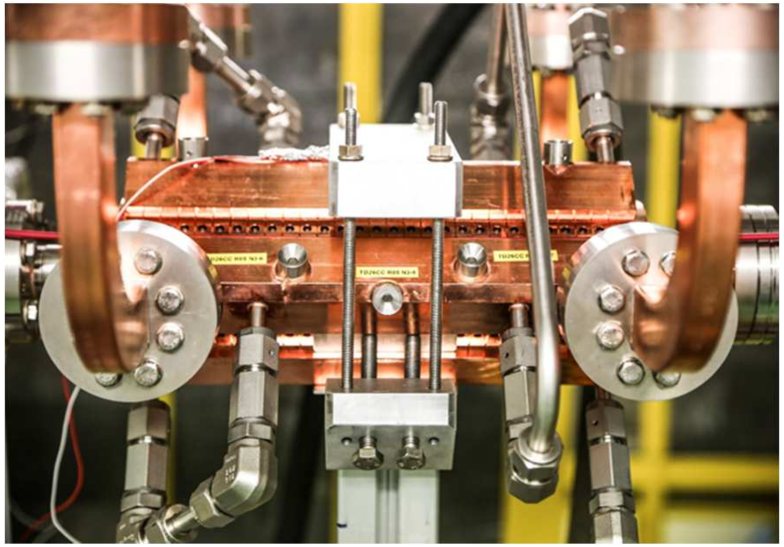
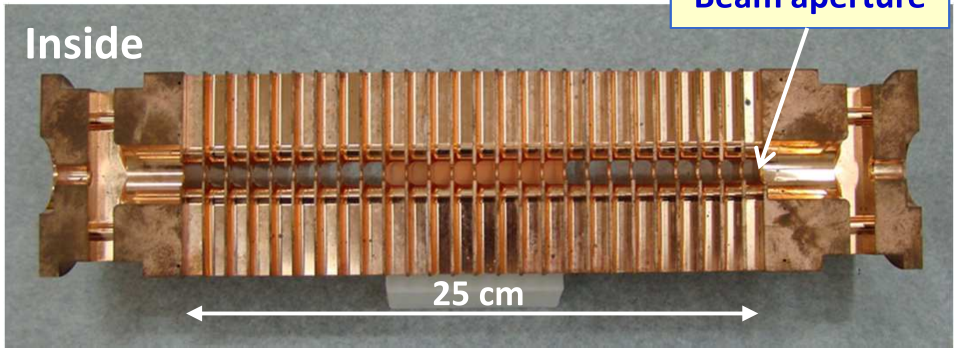
- f = 11.994 GHZ
- $E_{acc.}$ > 100MV/m
- Input power ~ 50 MW
- Pulse length ~ 200 nsec
- Repetition rate 50 Hz

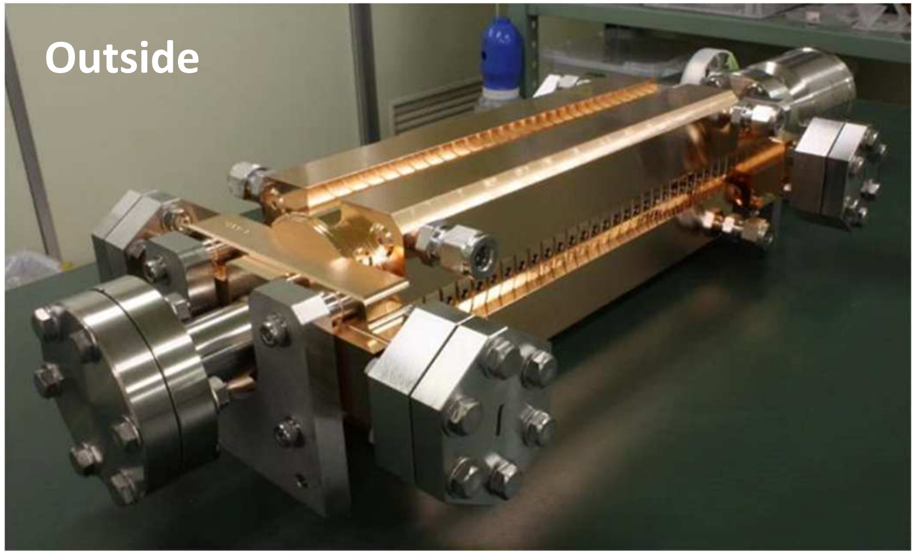


Micron–precision disk

HOM damping waveguide

6 mm diameter Beam aperture



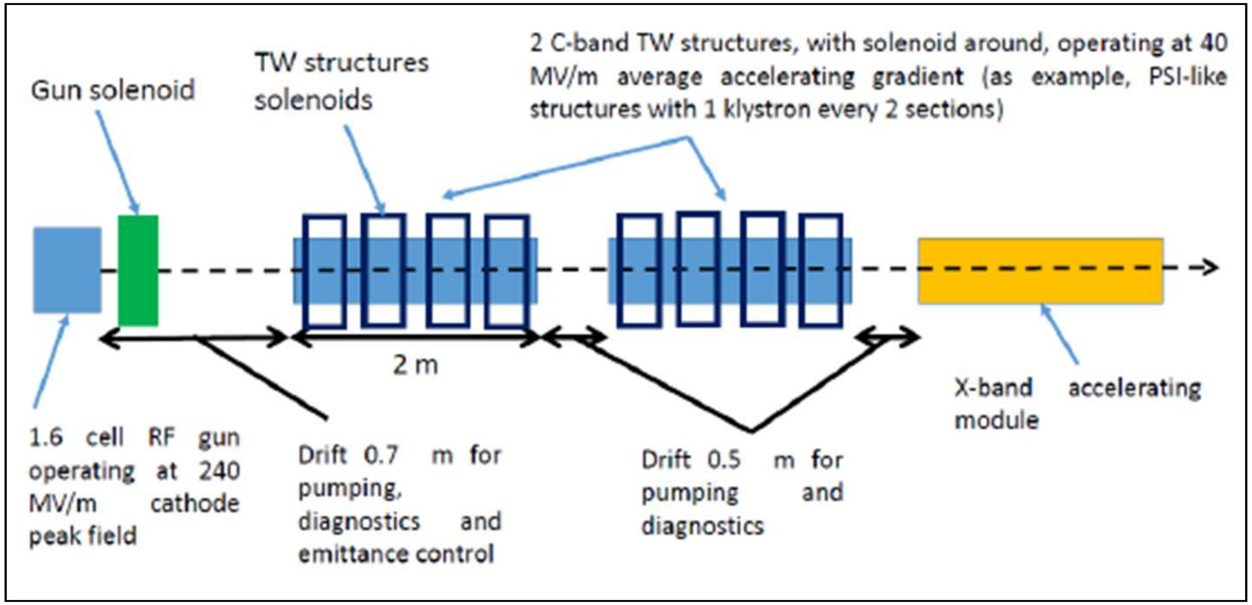


Courtesy
W. Wuensch

Injector

Parameters	Units	After VB and / or BC1
Charge (Q)	pC	75
Beam energy	MeV	300
rms bunch length (σ_t)	fs	350
Peak current ($Q/\sqrt{12}\sigma_t$)	A	60
rms Energy spread	%	0.5
Projected rms norm. emittance	μm	0.2
Repetition rate	Hz	100-1000

Expected bunch parameters at the injector exit

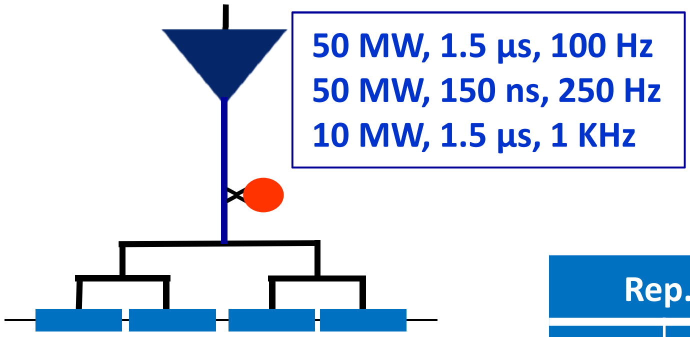


Schematic layout of the C-band injector

D. Alesini

XLS Accelerating structure XLS design

RF system parameter and layouts done for 100 Hz baseline, 100/250 Hz dual mode and 100/1000 Hz dual klystron



	Rep. rate [Hz]		
	100	250	1000
Average gradient <G> [MV/m]	65	32	30.4
Max klystron available out. power [MW]	50	50	10
Req. klystron power per module [MW]	39	42.5	8.5
RF pulse length [μs]	1.5	0.15	1.5
SLED	ON	OFF	ON
Av. diss. power per structure [kW]	1	0.31	2.2
Peak input power per structure [MW]	68	10.6	14.8
Av. Input power per structure [MW]	44	10.6	9.6
Module energy gain [MeV]	234	115	109

Parameter	Value
Frequency [GHz]	11.9942
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
Average iris radius <a>	3.5
Iris radius input-output [mm]	4.3-2.7
Structure length L_s [m]	0.9

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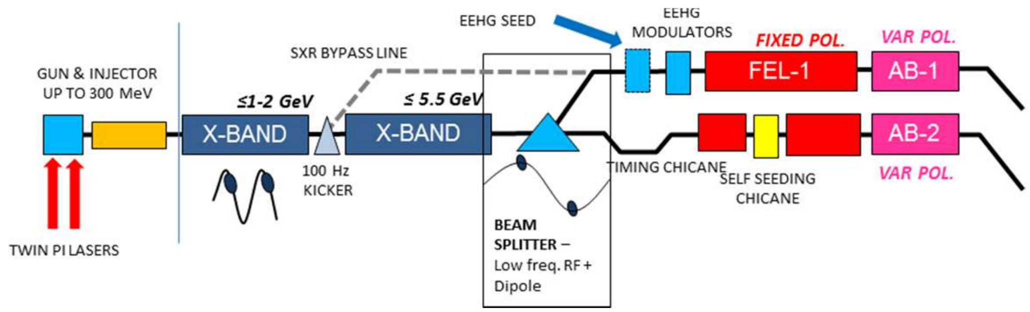
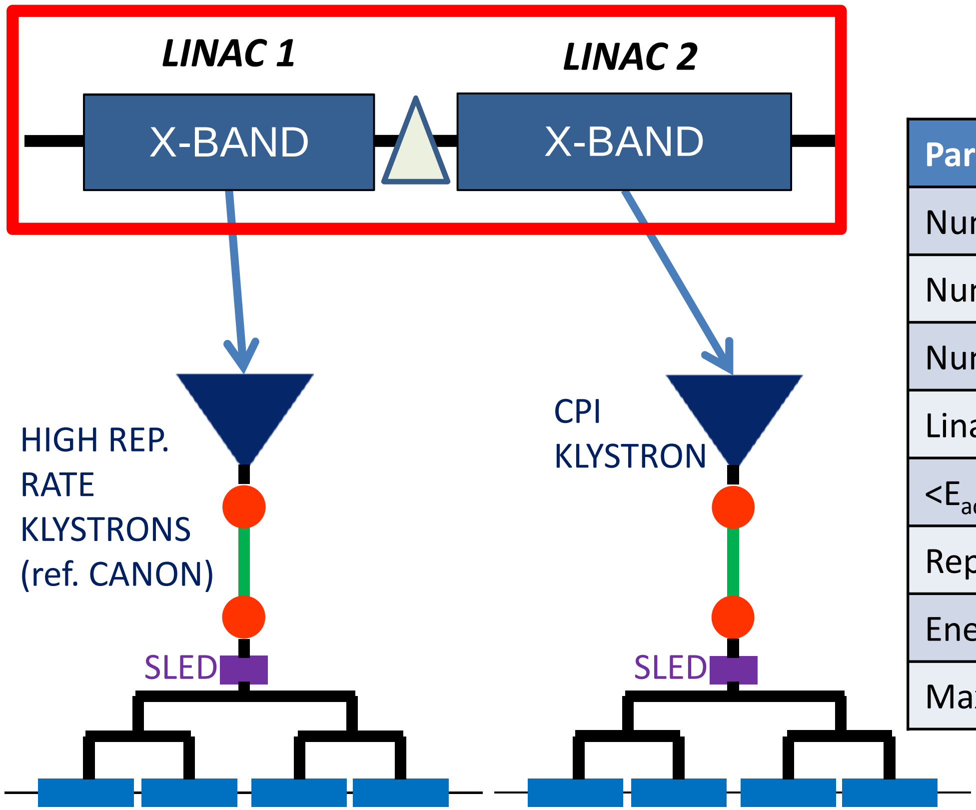
Operating modes: dual linac

- two distinct linacs with different rf sources
- SXR@ 1 kHz
- HXR@ 100 Hz
- SXR@ 900 Hz and HXR@ 100 Hz running in parallel





$\langle E_{acc} \rangle$ = 30.4 MV/m @ 1 kHz $\langle E_{acc} \rangle$ = 65 MV/m @ 100 Hz

Parameter	LINAC 1	LINAC 2	TOTAL
Number of structures	68	60	128
Number of modules	17	15	32
Number of klystrons	17 (HRR)	15 (CPI)	32
Linac active length [m]	61	54	137
$\langle E_{acc} \rangle$ per struct. [MV/m]	30.4	65	-
Rep. rate [Hz]	1000	100	-
Energy gain per module [MeV]	109	234	-
Max. Energy gain [MeV]	1853	3510	5363

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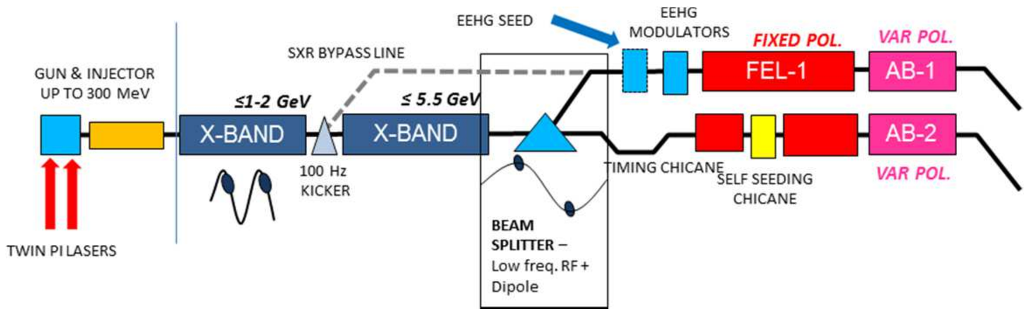
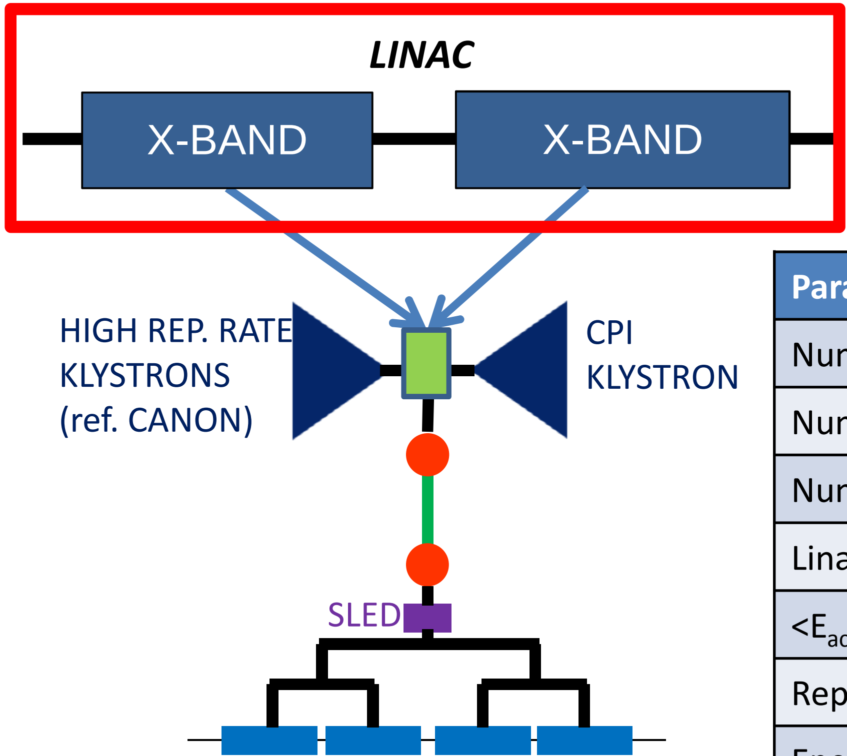
Operating modes: dual sources

- Single linac with two sources
- SXR@ 1 kHz
- HXR@ 100 Hz
- SXR and HXR CANNOT run in parallel





$\langle E_{acc} \rangle$ = 30.4 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 (HRR) + 23 (CPI)**
Linac active length [m]	**83**
$\langle E_{acc} \rangle$ per struct. [MV/m]	**30.4 (@1 kHz), 65 (@ 100 Hz)**
Rep. rate [Hz]	**100-1000**
Energy gain per module [MeV]	**109 (@1 kHz), 234 (@ 100 Hz)**
Max. Energy gain [MeV]	**2507 (@1 kHz), 5382 (@ 100 Hz)**

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Towards higher rep rate operation

Different scenarios under investigations:

1st scenario (1 klystron x LINAC Module): **RF pulse shortening**

50 MW, 1.5 μs, 100 Hz $\langle E_{acc} \rangle$ = 65 MV/m	→	50 MW, 140 ns, 220 Hz $\langle E_{acc} \rangle$ = 30 MV/m

- Linac energy downgraded to ≈ 45% of the max value @ 220 Hz rep rate;
- Not flexible: as soon as the SLED is removed the gradient is reduced by a factor ≈2.2;
- Max rep rate very much dependent on modulator dead time τ_{trans}

2nd scenario (1 klystron x LINAC Module): **klystron peak power reduced**

50 MW, 1.5 μs, 100 Hz	→	**1.5 μs, 10 MW, 200 Hz** **1.5 μs, 5 MW, 250 Hz**	→	**$\langle E_{acc} \rangle$ = 29 MV/m @ 200 Hz** **$\langle E_{acc} \rangle$ = 20.5 MV/m @ 250 Hz**

- Linac energy downgraded to ≈ 30% of the max value @ 250 Hz rep rate;
- Flexible: different compromises between rep rate and RF peak power explorable;
- Klystron operated in a wide range of working points (realistic?)

3rd scenario (2 klystrons x LINAC Module): **- high rep rate/reduced peak power klystrons**
- low rep rate/HP klystron

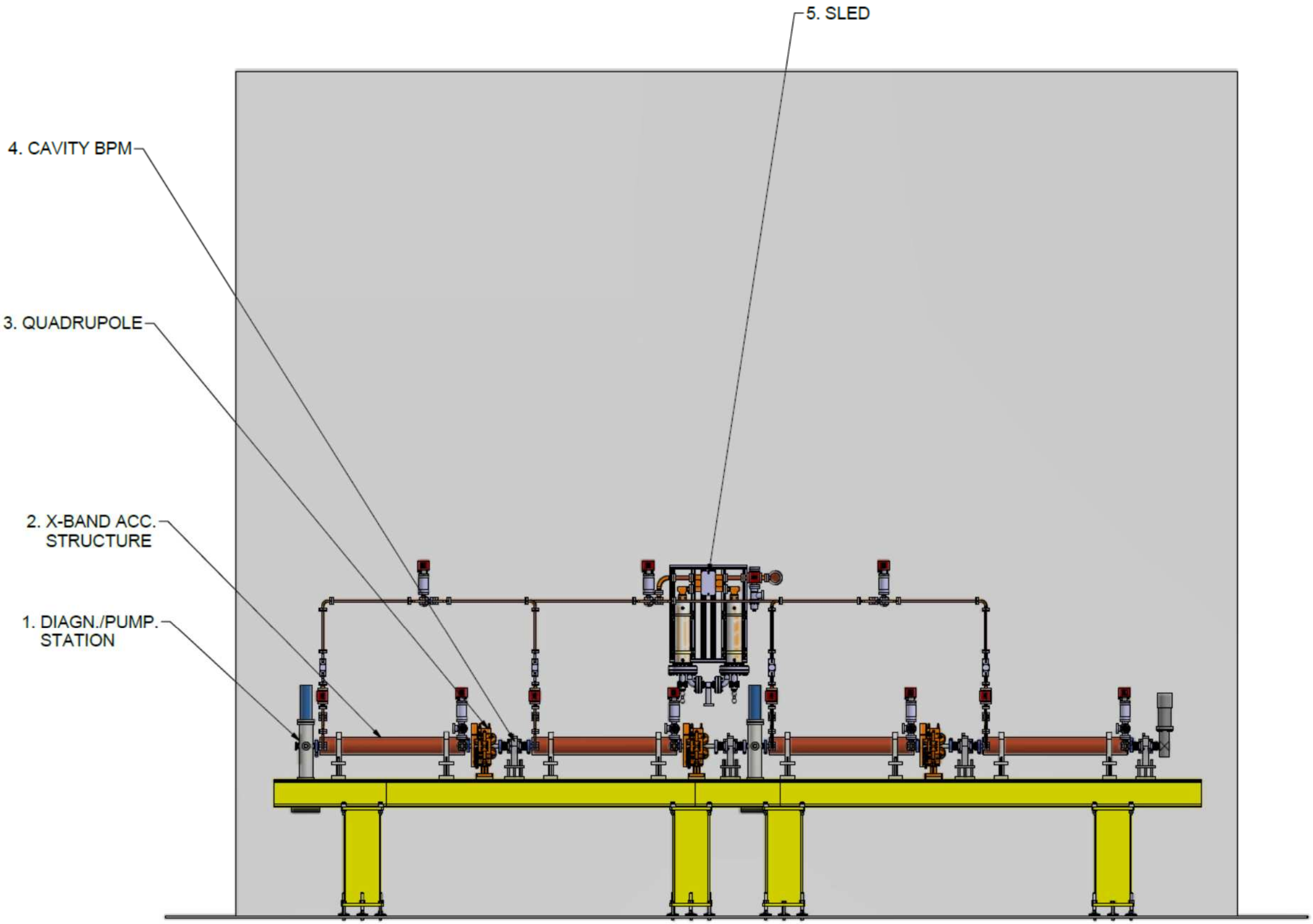
CANON E37113 klystron, 6 MW 1.5 μs, 1 KHz + CPI VKX 8311A	→	$\langle E_{acc} \rangle$ = 65 MV/m @ 100 Hz $\langle E_{acc} \rangle$ = 23 MV/m @ 1 kHz

- …………?????

More detailed studies ongoing

A. Gallo

RF module



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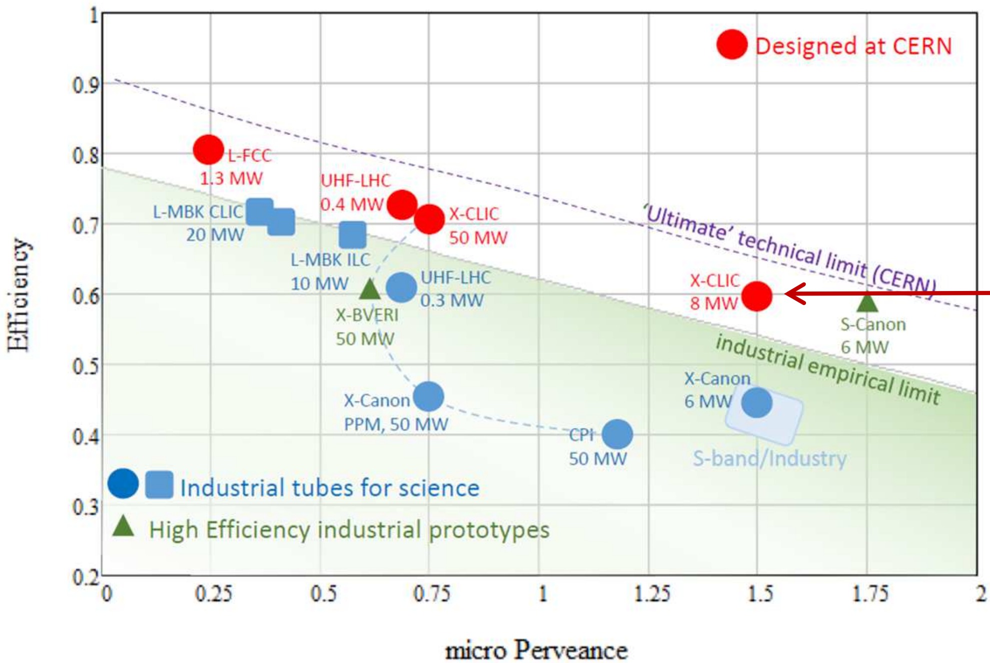
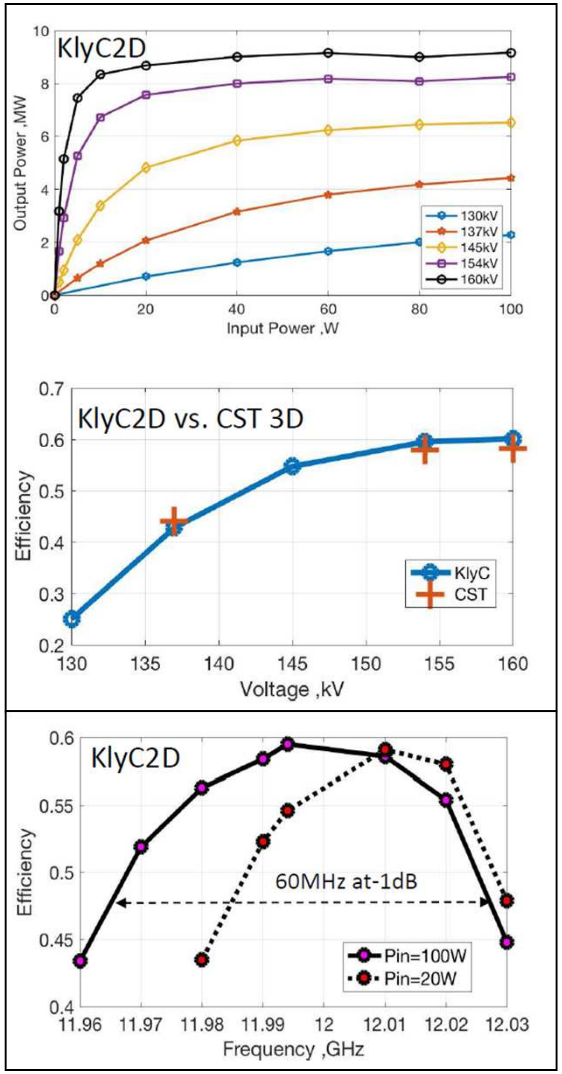
High efficiency klystrons

Klystron efficiency/perveance map



8-9 MW X-band klystron from industry



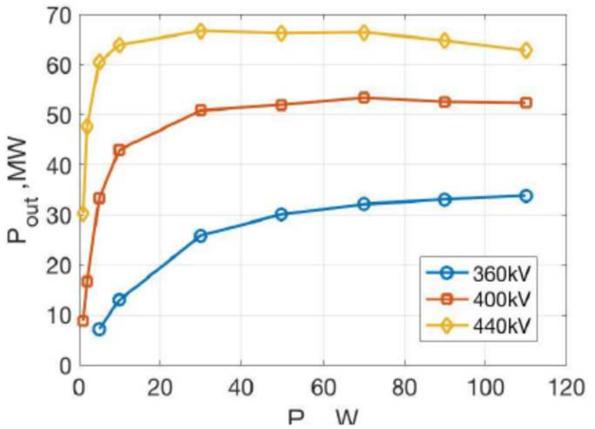
- **The HE retrofit design shall provide up to 10 MW (170 kV) peak RF power**.
- The existing gun is re-used, thus in DC mode the limits on avarage power will be similar. **With 2.5 µsec pulses** (typical in Xbox3 with pulse compressor), **the rep rate could be doubled (800 Hz)** with out any modifications.
- **With intellegent operation (rep. rate shall be reduce when switching from RF to DC mode)**, the 1.5 kHz will accesible without modificationson of the klystron design.
- **Special care shall be given to the window design that shall to be adopted to the high avarage power.**

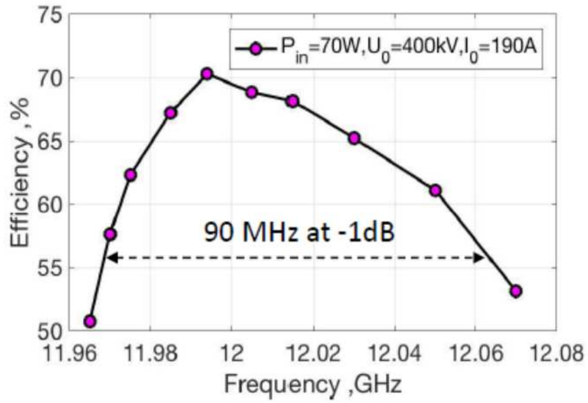
I. Syratchev, J. Cai

High efficiency klystrons

The 50 MW HEX klystron progress summary

Parameter	Target value	KlyC/2D
Frequency, GHz	11.994	11.994
Voltage, kV	400	400
Current, A	190	190
Perveance, $\mu AV^{-3/2}$	0.75	0.75
Efficiency, %	~70	**70.2**
Power, MW	53	**53.4**
Surface E field, MV/m	≤ 100	**<100**
Pulse length, ns	2000	2000
Power gain, dB	> 55	**58.8**
Cathode loading, A/cm^2	< 5	**4.74**





The final design is communicated to industry (CPI) for the final evaluation.

The HE design has lower (almost a factor 2) beam power for the same peak RF output power. The rep. Rate can be double (200Hz) in straightforward way without any modifications of collector and/or cooling system

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Thank you!

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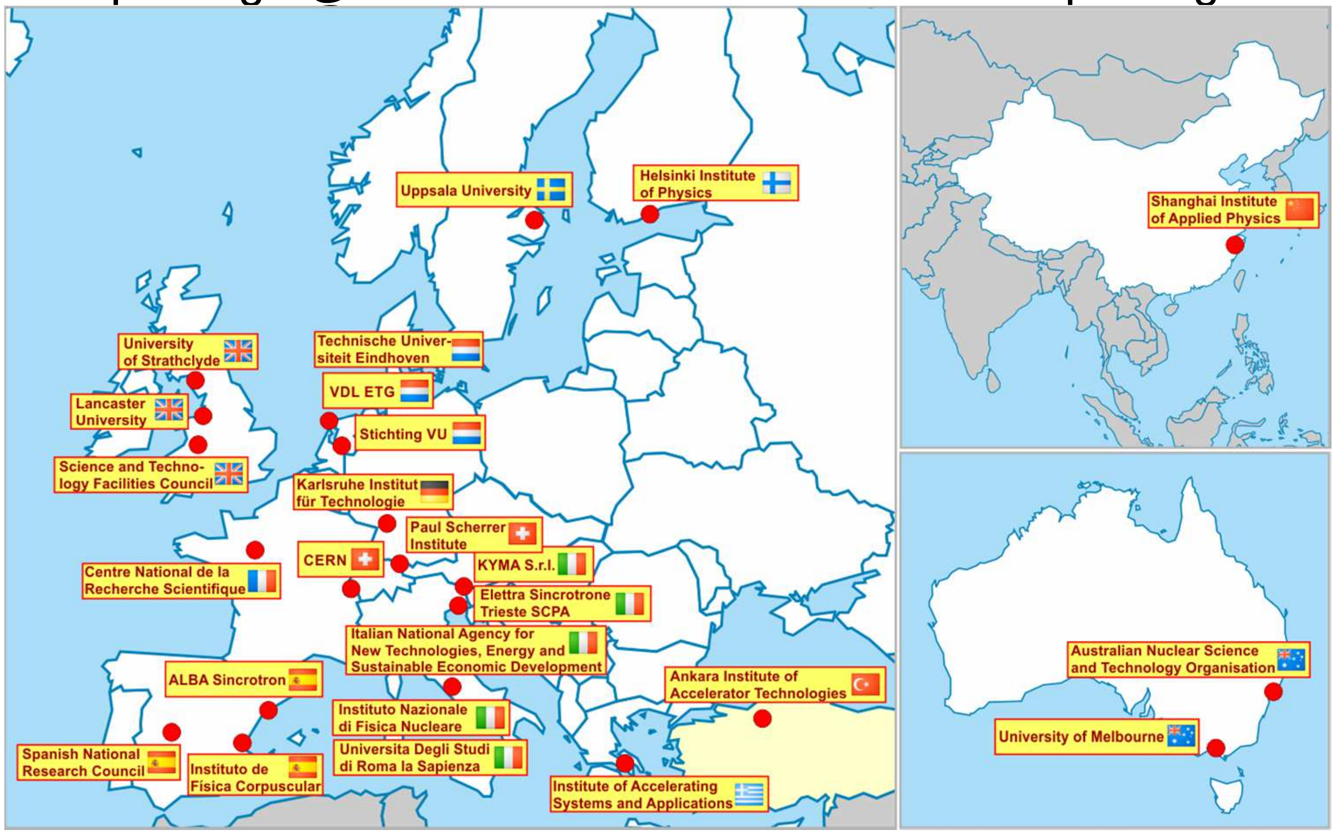

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