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Compact

S, C, X, and Ka-band rf systems in CompactLight

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Outline

1. Introduction to CompactLight

2. C-band rf system: RF gun and injector design

3. Ka-band rf system: Harmonic linearising structure design

4. X-band rf system: Main linac structure design

5. S-band rf system: Sub-harmonic transverse deflector system design

6. Diagnostic system: PolariX TDS

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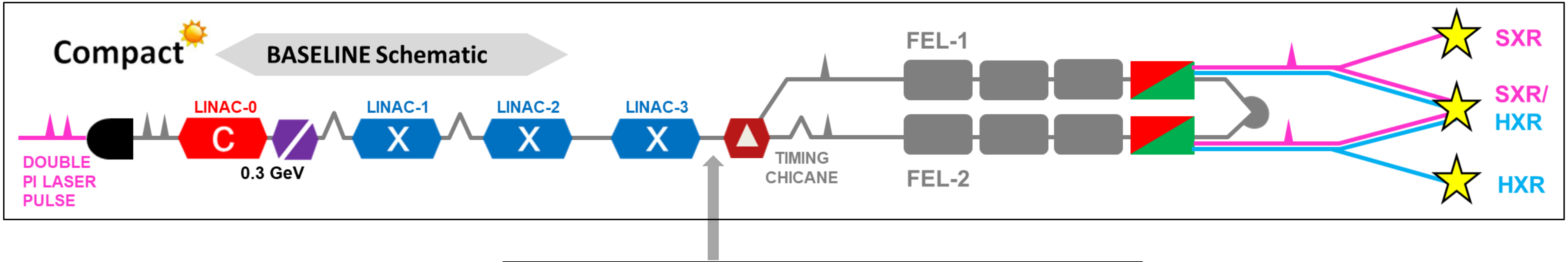
Layout of CompactLight

Compact



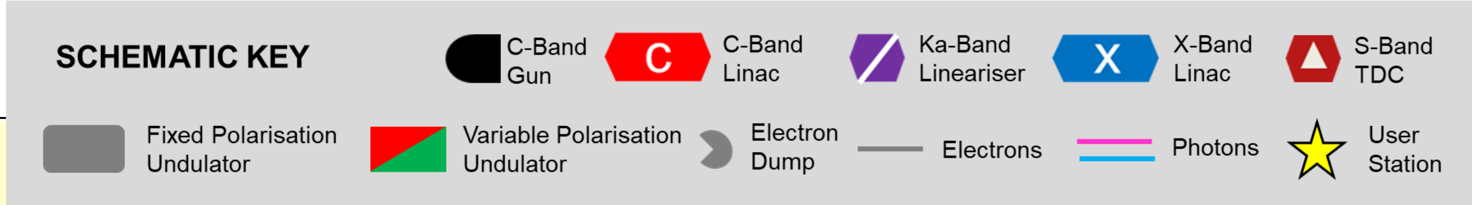
BASELINE	**0.97 to 2.4 GeV @ 250 Hz (SXR/SXR)** **2.75 to 5.5 GeV @ 100 Hz (HXR/HXR)**
UPGRADE1	**0.97 to 2.4 GeV @ 1000 Hz (SXR/SXR)** **2.75 to 5.5 GeV @ 100 Hz (HXR/HXR)**

A compact free electron laser project based on X-band technology

Two-bunch operation for pump-and-probe experiment

Produce **100 Hz hard X-ray** (2.0 - 16.0 keV) and **1000 Hz soft X-ray** (0.25 - 2.0 keV) with same installed linac

Design project funded by European Union Horizon 2020



* Courtesy by N. Thompson

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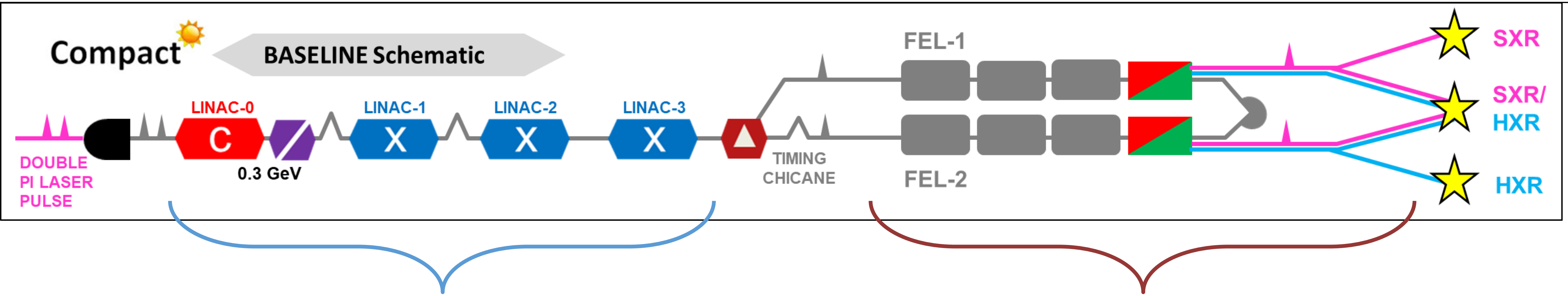
Layout of CompactLight



Main linac

Length~ 216 m

FEL lines

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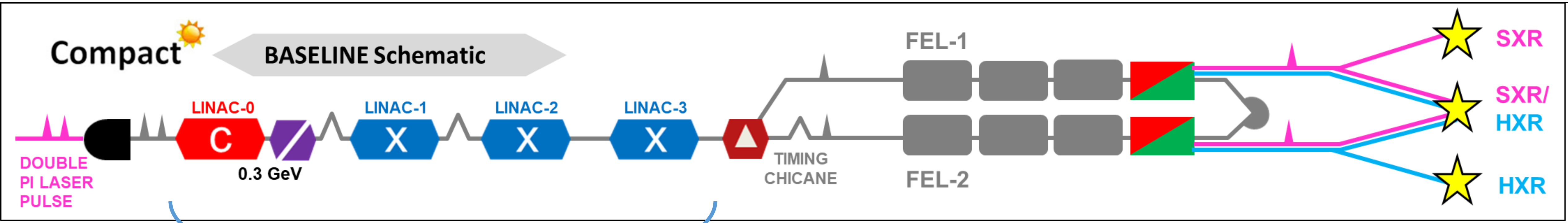
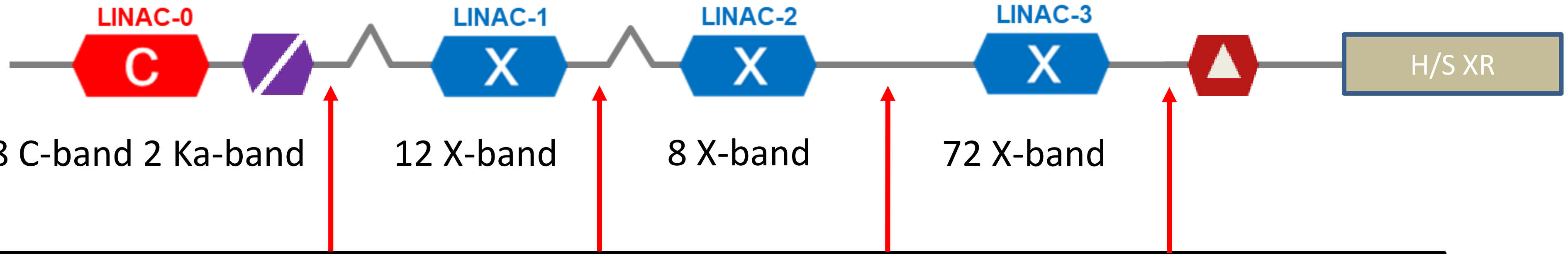
Linac layout



X-band accelerating structures operate at different gradients for 100 and 1000 Hz

Main linac



100 Hz	300 MeV	0.98 GeV	1.43 GeV	**5.50 GeV**	→ hard X-ray
1000 Hz	300 MeV	0.57 GeV	0.76 GeV	**2.40 GeV**	→ soft X-ray

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Main Linac of CompactLight

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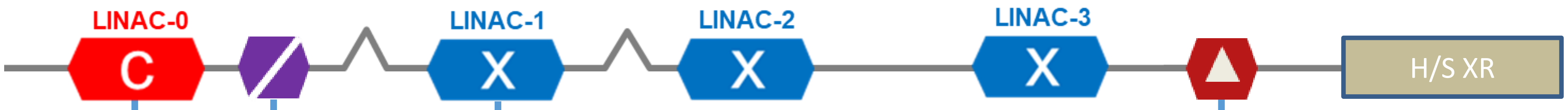


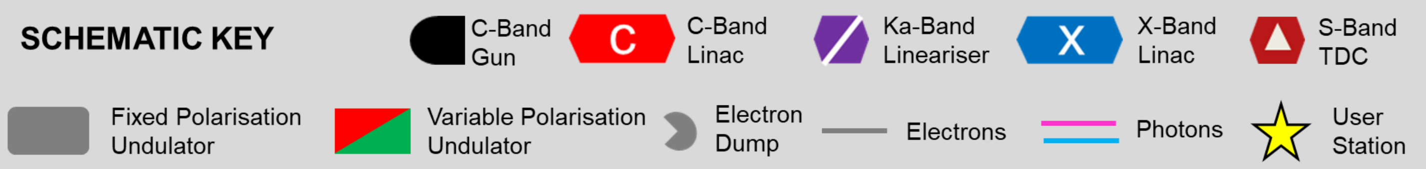
C-band rf system: RF gun and injector

Ka-band rf system: Harmonic linearising structure

X-band rf system: Main linac structure design

S-band rf system: Sub-harmonic transverse deflector system design

Diagnostic system: PolariX TDS



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Full C—band XLS Injector Compact

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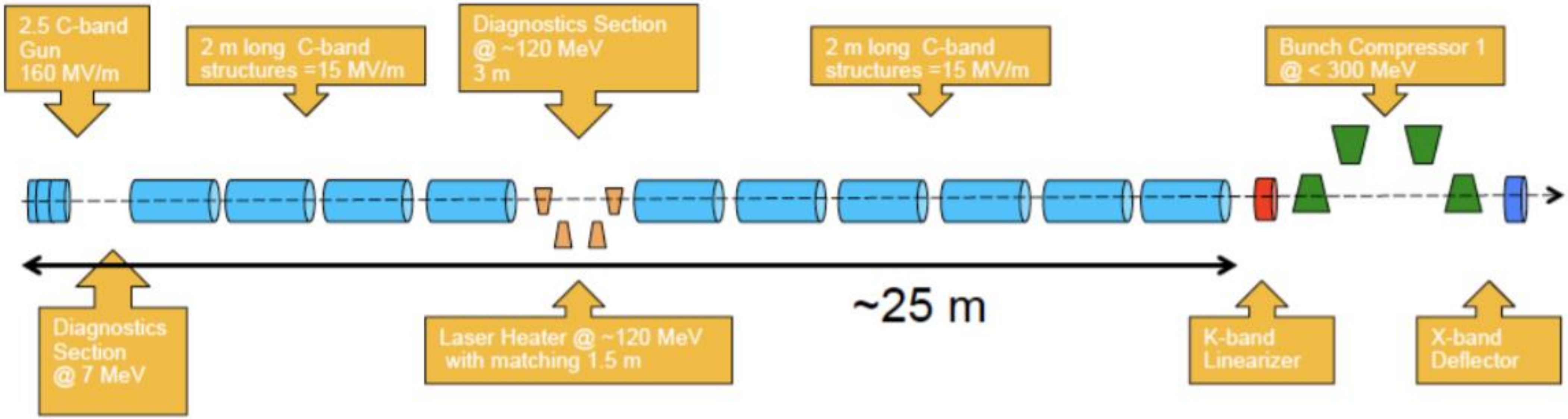
* Courtesy by C. Vaccarezza

- One injector for all the operational modes (HRR and LRR)
  - 2.5 C-band gun with 160 MV/m cathode peak field => longer drift for diagnostics
  - Copper cathode and TiSa Laser
  - Same gradients 15 MV/m in the 2 m long C-band structures, max gain 30 MeV/structure
  - Same diagnostics positions (@ gun exit 7 MeV and in the drift parallel to the LH @ 120 MeV)
  - Same beam parameters at the linac exit
  - Matching with LH to be determined



- Optimal BC1 input energy (=> and position) to be determined
  - Without Velocity Bunching
  - With Laser Heater less than 2 m long
  - K-band Linearizer just before the BC1, X-band RFD downstream BC1
  - Same beam parameters at the BC1 exit

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X + C—band XLS Injector

Compact

* Courtesy by C. Vaccarezza

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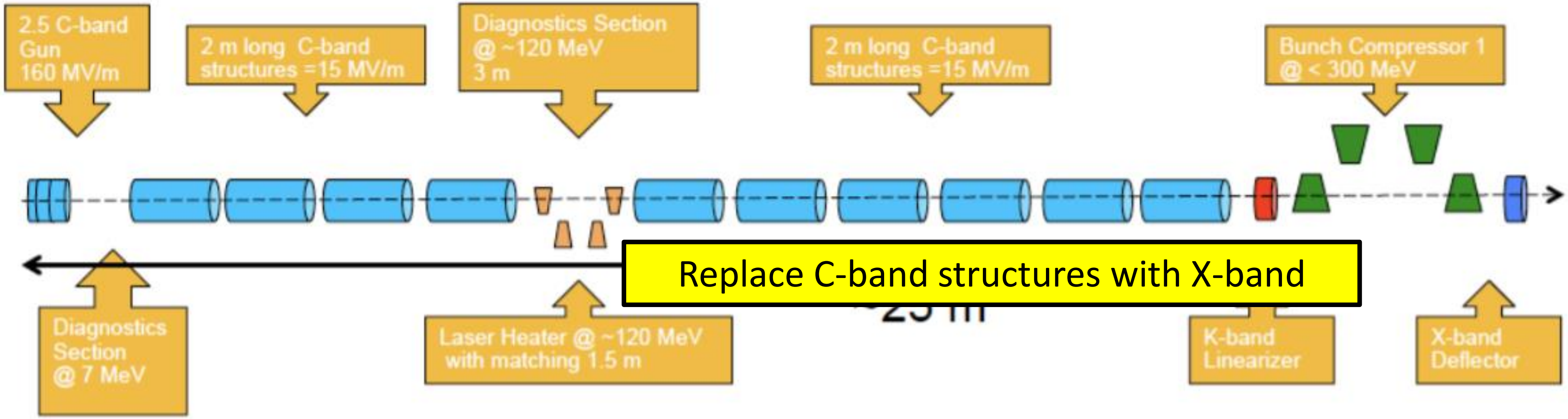

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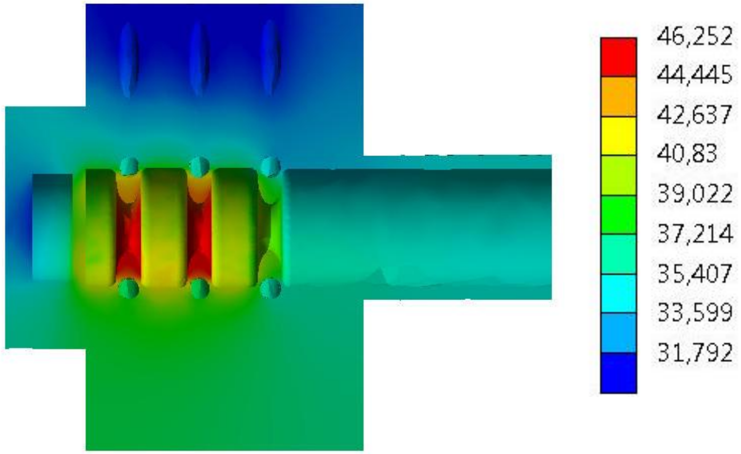
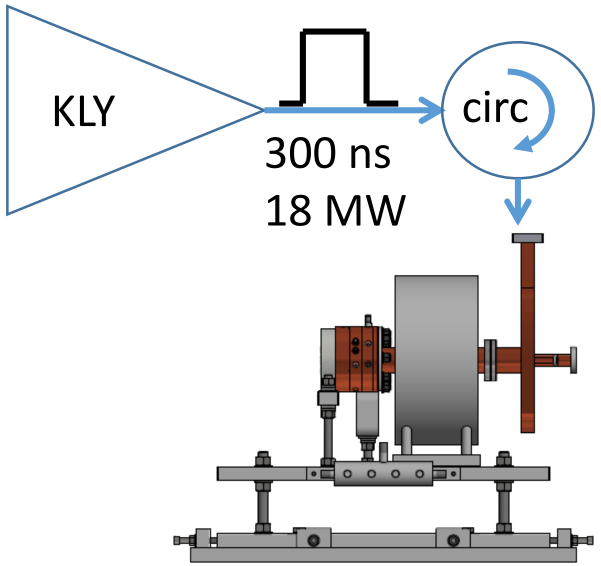
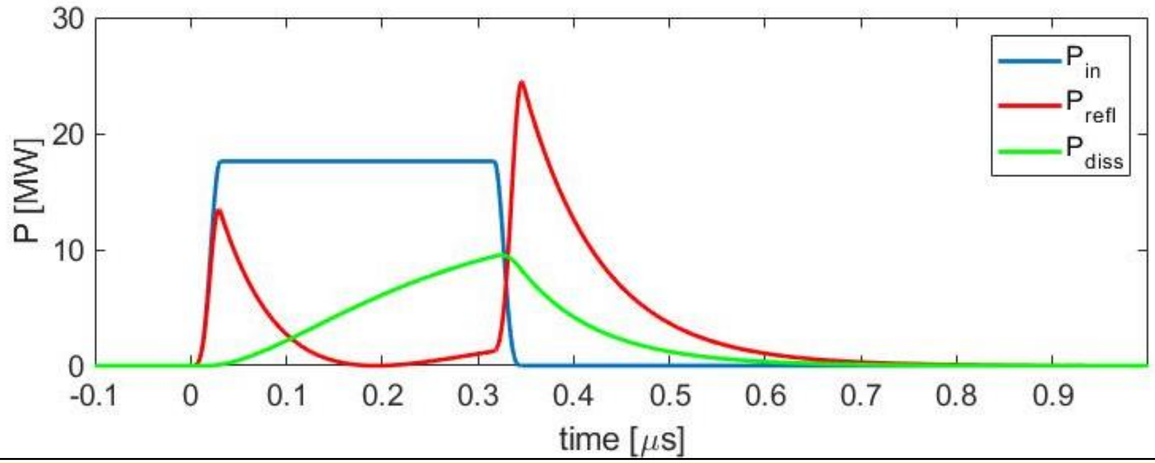
C-band gun design

* Courtesy by D. Alesini

- ⇒ Powered with **short pulses** (300 ns) of few tens of MW to reduce the pulsed heating ($\sim\sqrt{\tau}$) and BDR ($\sim\tau^5$);
- ⇒ Design compatible with **1 kHz rep. rate**;
- ⇒ **Cathode peak field (E_{cath}): 160 MV/m** ;







E_{cath}	160 MV/m
$\Delta f_{\pi/2-\pi}$	≈ 52 MHz
Q_0	11600
β	3
Filling time (τ_F)	160 ns
P_{diss} @160MV/m	9.7 MW
$E_{CAT}/\sqrt{P_{diss}}$	51.4 [MV/m/(MW)$^{0.5}$]
Rep. Rate	1000 Hz
Peak Input power P_{IN}	18 MW
Pulsed heating (T_{puls})	<20 °C
RF pulse length (T_{RF})	300 ns
Av diss power (P_{av})	2300 W

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C-band module with Barrel Open Cavity (BOC)

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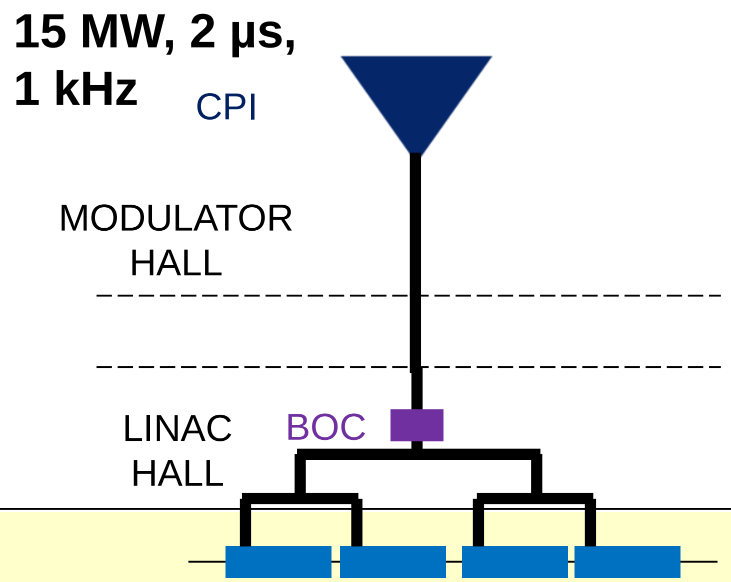
2 m long PSI-like C-band structure designed by INFN

* Courtesy by M. Diomede

RF System	
Operating frequency [GHz]	5.996
Klystron pulse length [us]	2
Klystron peak power [MW]	15
Pulse rate [pps]	1000
Q0 of BOC	216000
Qe of BOC	19100



Acc. Structure	
Phase advance	2pi/3
Cell length [mm]	16.667
Number of cells	120
Total length [m]	2
Average iris radius [mm]	6.6
Tapering angle [deg]	0.02
Iris radius (first - last) [mm]	6.943 – 6.257
Shunt imp. [MΩ/m]	71 - 77
Q	9986 - 9943
Group velocity/c [%]	2.4 – 1.6
Filling time [ns]	336
Repetition rate [Hz]	1000
Avg. acc. gradient [MV/m]	**15**

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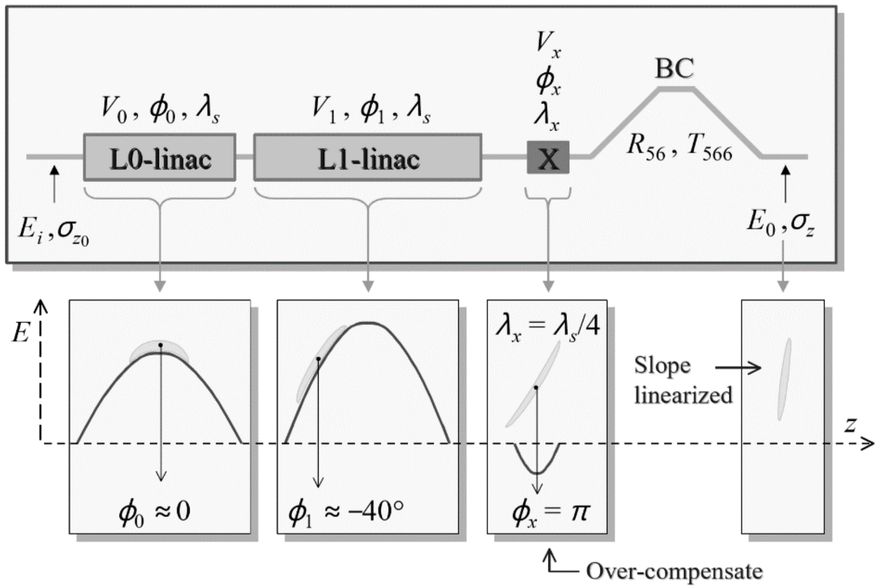
Background of Lineariser

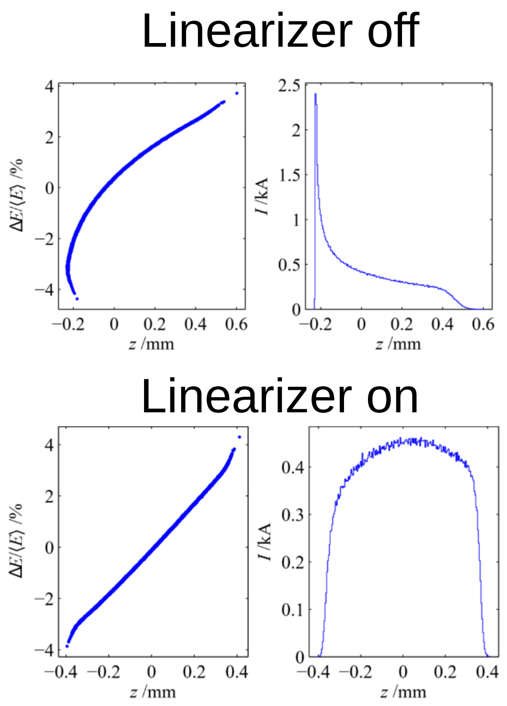
Linearise the bunch compression process in XFEL by RF harmonic compensation

- correct the longitudinal phase space non-linearity from the injector
- C-band (potentially updated to X-band) injector drives the harmonic frequency to be **36 GHz at Ka-band**
- higher harmonics are more efficient for second-order compensation, decelerating the beam less

$$V \propto \frac{1}{\left(\frac{f_L}{f_a}\right)^2 - 1}$$

f_L : Linearizer
f_a : Linac





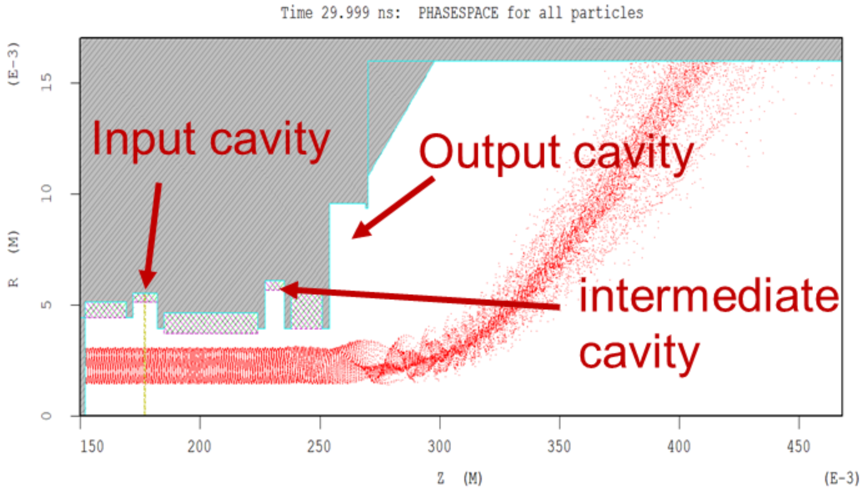
Emma, Paul. No. SLAC-TN-05-004. SLAC, Menlo Park, CA, 2005.

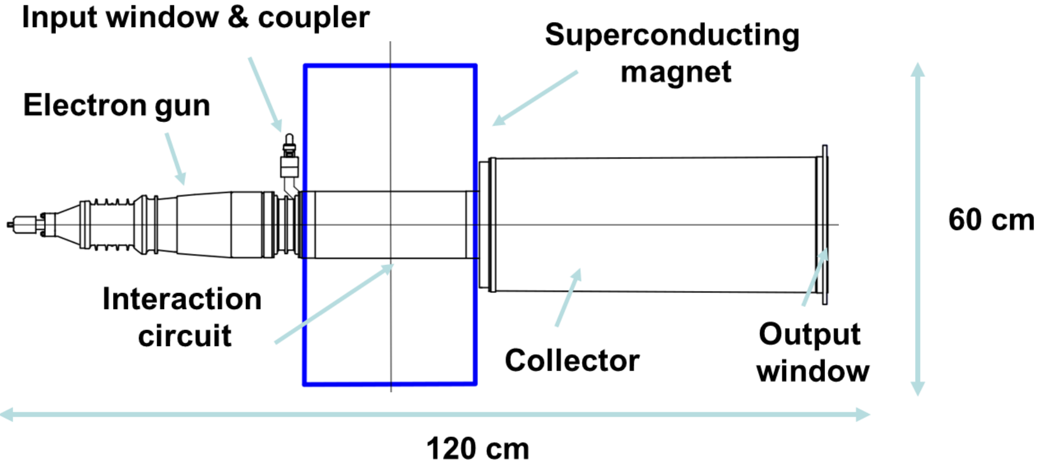
rf sources at Ka-band

* Courtesy by G. Burt

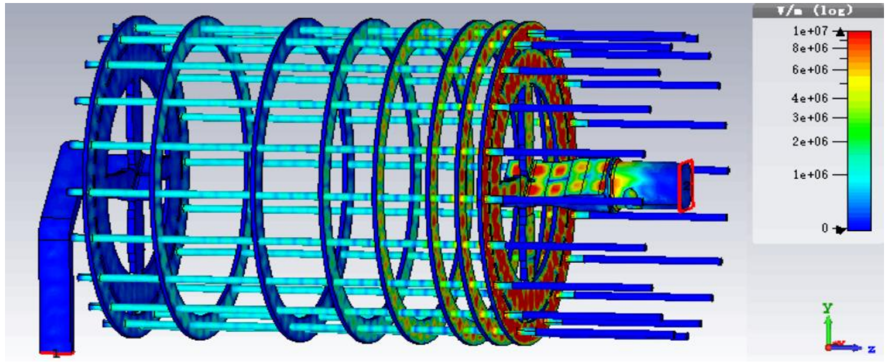
Two possible designs, gyro-klystron and multi-beam klystron, could provide ~3 MW at 1 kHz

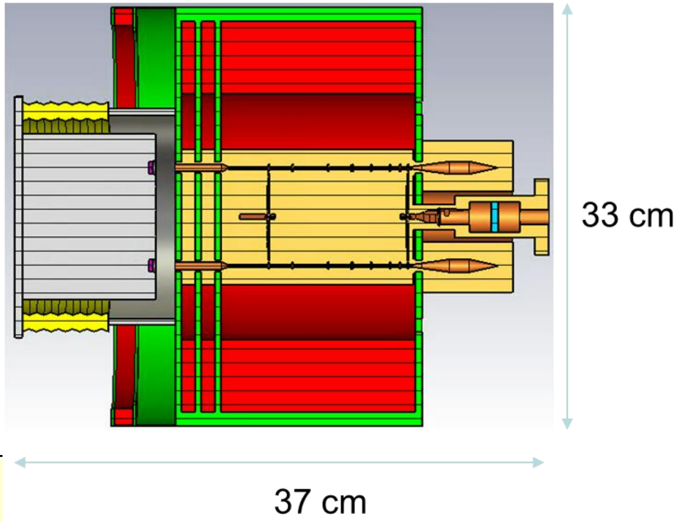
Gyro-klystron





Multi-beam klystron





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Pulse compression at 36 GHz

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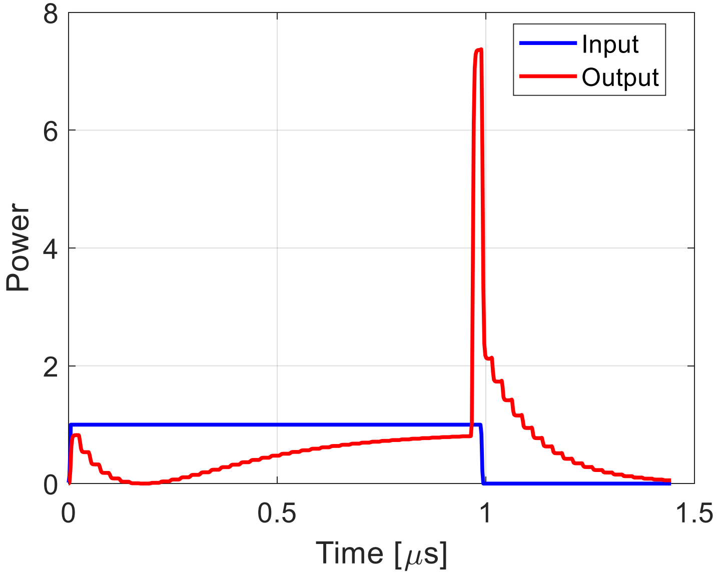
TE01&TE02 dual-moded SLEDII pulse compressor

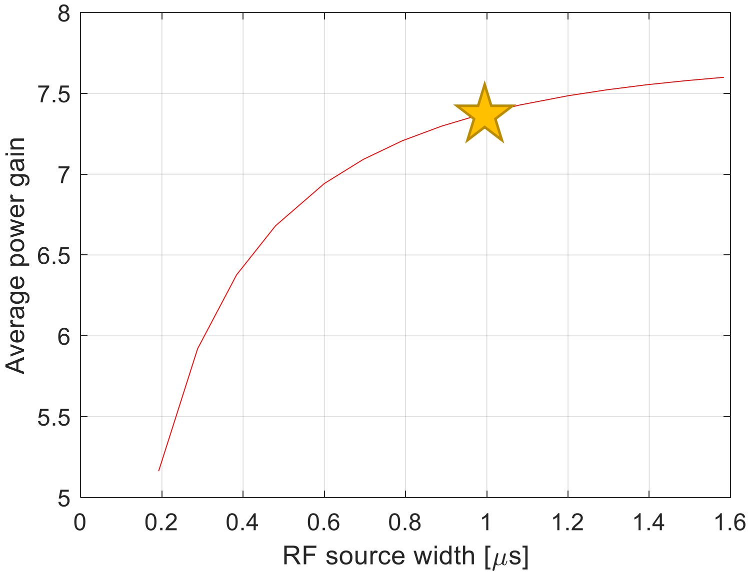
Radius of the delay line = 25 mm

Length of the delay line = 1.71 m

984 ns 2.27 MW rf source pulse width →**24 ns 15.9 MW** compressed pulse

SLED II at CTF3





RF source width [ns]	Compression ratio	Power gain (average)	Compressed Power
192	8	5.16	11.1456
288	12	5.92	12.7872
384	16	6.38	13.7808
480	20	6.68	14.4288
600	25	6.94	14.9904
696	29	7.09	15.3144
792	33	7.21	15.5736
888	37	7.30	15.768
984	41	7.37	15.9192
1080	45	7.43	16.0488
1200	50	7.49	16.1784

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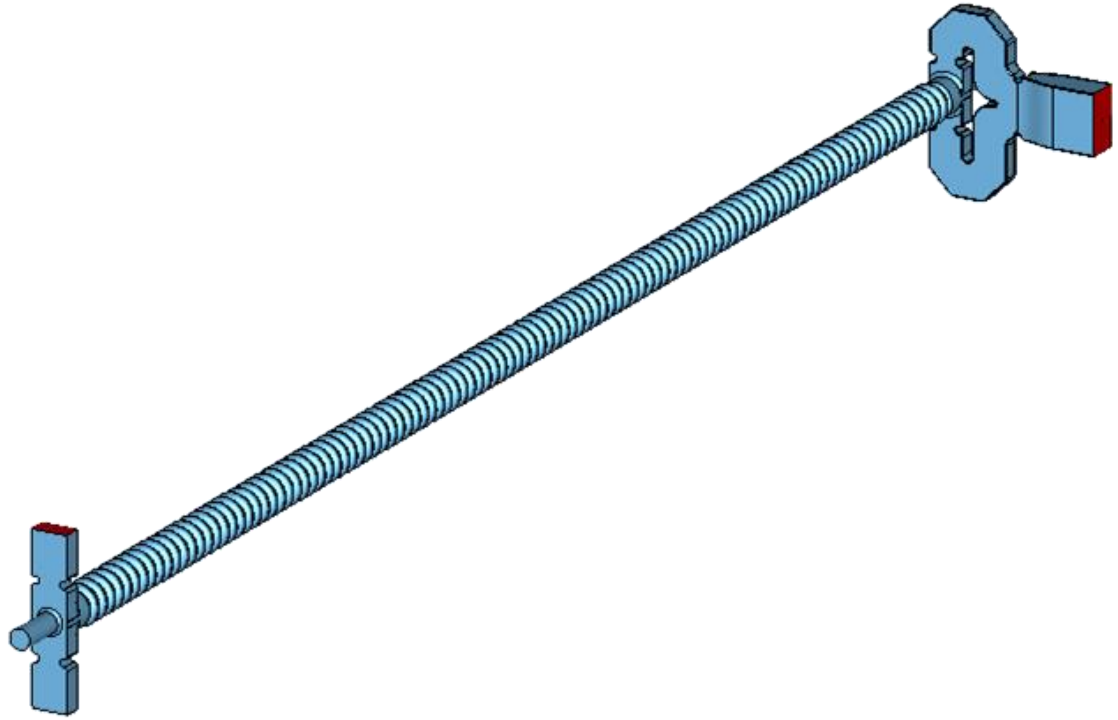
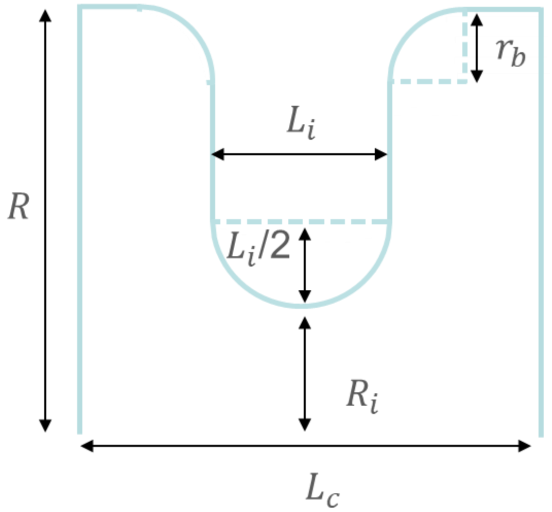
Travelling-wave linearising structure at 36 GHz

* Courtesy by G. Burt and A. Castilla

A 2π/3 30 cm structure provides the required voltage (12.75 MV) with the 15 MW of RF power supplied by the RF source and pulse compressor

- 1x 30cm with 15 MW for 12.5 MV (41.7 MV/m)
- Maximum surface E field is 108 MV/m





Parameter	$\varphi = {}^{2\pi}/_3$	$\varphi = {}^{5\pi}/_6$	$\varphi = {}^{6\pi}/_7$	Units
Freq.	36			GHz
Q	4392	5251	5365	--
r_L	106	109	109	MΩ/m
v_g	0.122	0.138	0.145	c
α_0	0.7	0.5	0.5	m^{-1}
E_p^*	2.6	3.1	3.0	MV/m
R	3.96	3.86	3.85	mm
R_i	2.00			mm
L_c	2.78	3.47	3.57	mm
L_i	0.60			mm
r_b	1.00			mm

*normalized to $E_z = 1\ MV/m$

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Baseline X-band module layout

* Courtesy by M. Aicheler

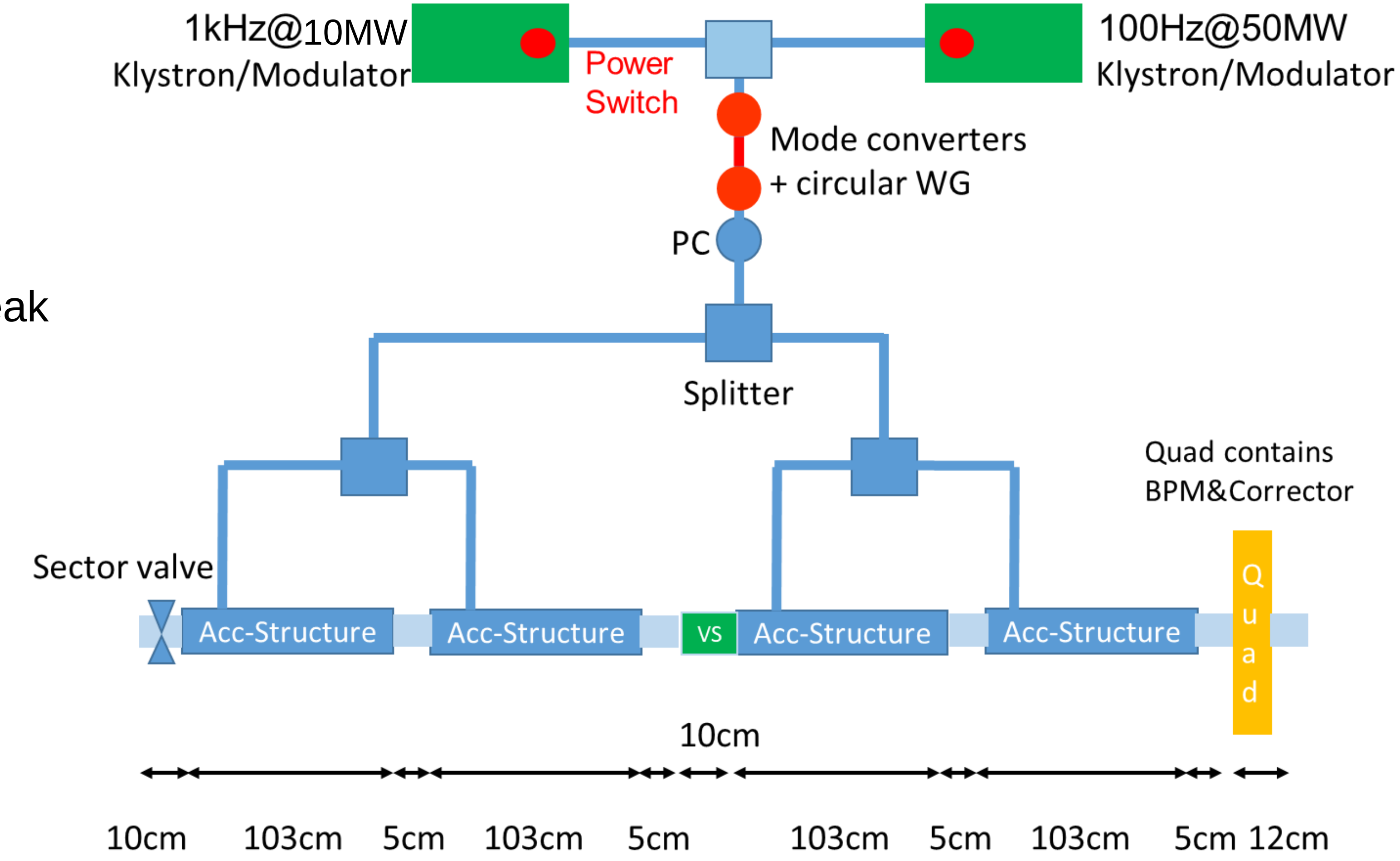
4 X-band structures in 1 rf module

Dual rf source (100 Hz and 1000 Hz)

With pulse compressor to increase the peak power

Module energy gain: 234 MeV@100 Hz

109 MeV@1000 Hz



Module length: 4.69 m; rf-fill factor: 77%

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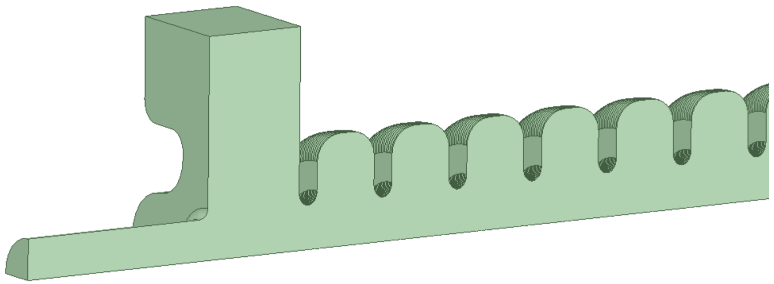
CompactLight X-band structure

108-cell $2\pi/3$ traveling-wave structure designed by INFN

* Courtesy by M. Diomede

Parameter	Value
Frequency [GHz]	11.9942
Phase advance per cell [rad]	$2\pi/3$
Shunt impedance R [MΩ/m]	90-125
Effective shunt Imp. R_s [MΩ/m]	378
Group velocity v_g [%]	4.7-0.9
P_{out}/P_{in}	0.215
Filling time [ns]	146
Number of cells per structure	108
# 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



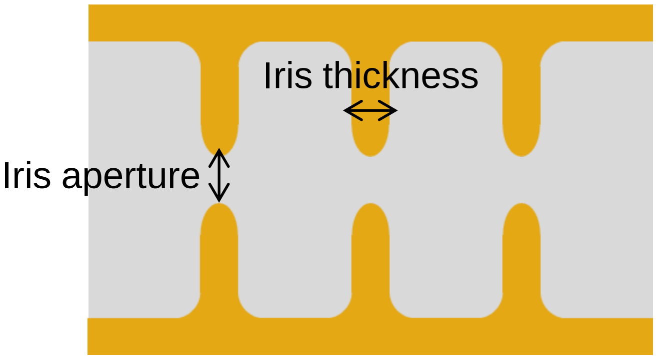
	Rep. rate [Hz]		
	100	250	1000
Average gradient <G> [MV/m]	**65**	**32**	**30.4**
Max klystron available output power [MW]	50	50	10
Required input power per module P_K [MW]	39	42.5	8.5
RF pulse [µs]	1.5	0.15	1.5
SLED	ON	OFF	ON
Av. diss. power per structure [kW]	1	0.31	2.2
Peak input power per structure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

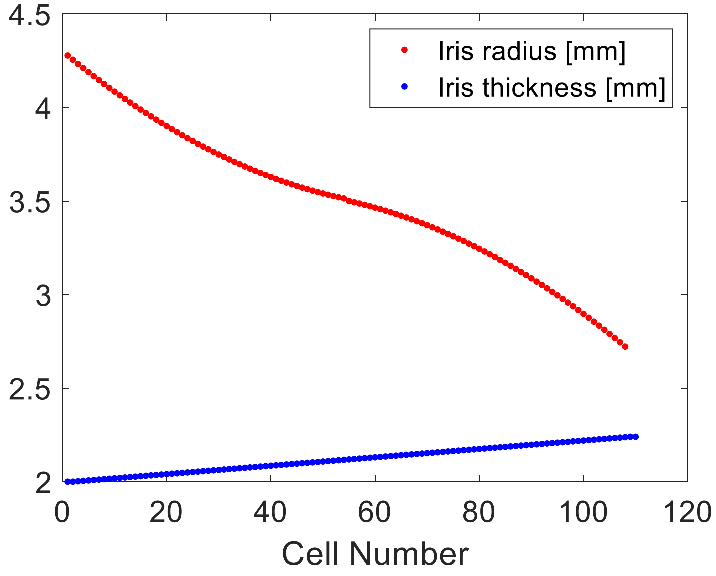
Long-range wakefield consideration for two-bunch operation

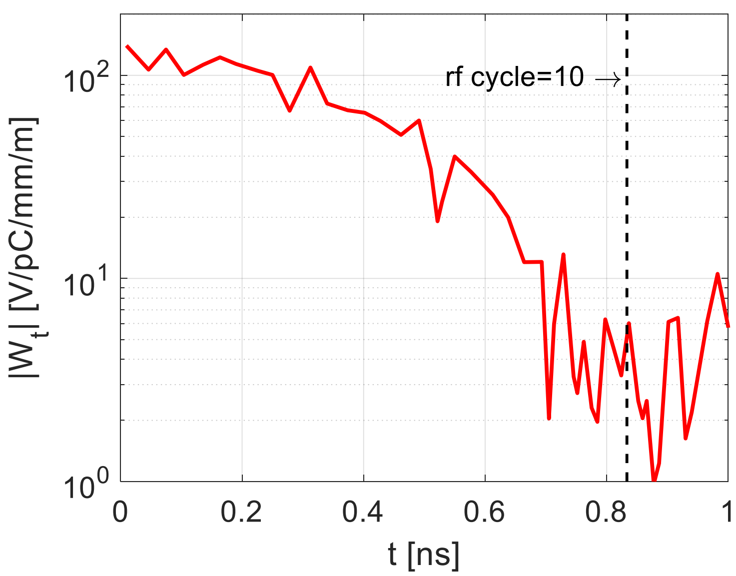
CompactLight is an XFEL project with **two-bunch operation** for pump-probe experiment

Linear iris thickness distribution and Gaussian-like aperture distribution are applied to reduce the wakefield to ensure the two-bunch operation

10 X-band rf cycles are chosen to be the bunch spacing

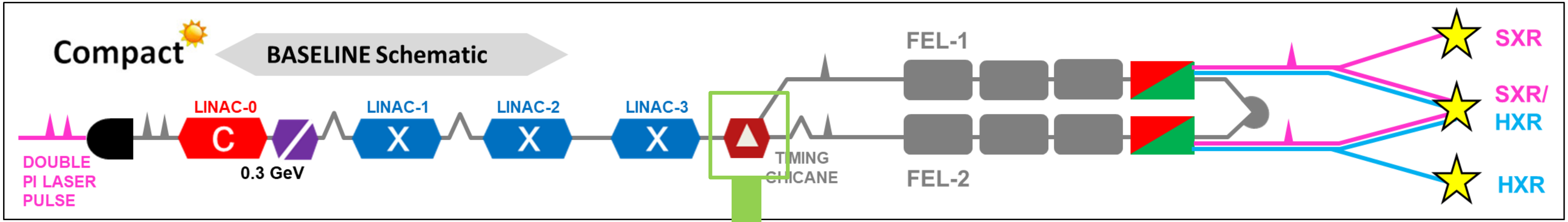






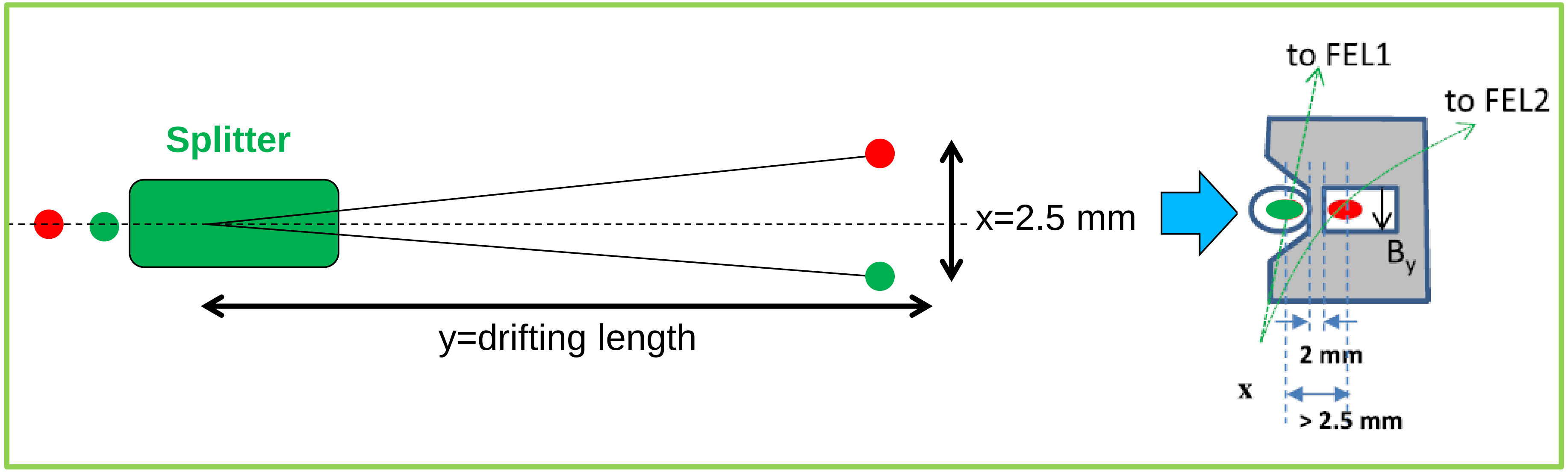
Outline

Bunch splitter before FEL structure



Need a splitter to separate the two bunches into two FEL lines

Distance between the two bunches should be over 2.5 mm at the entrance of septum



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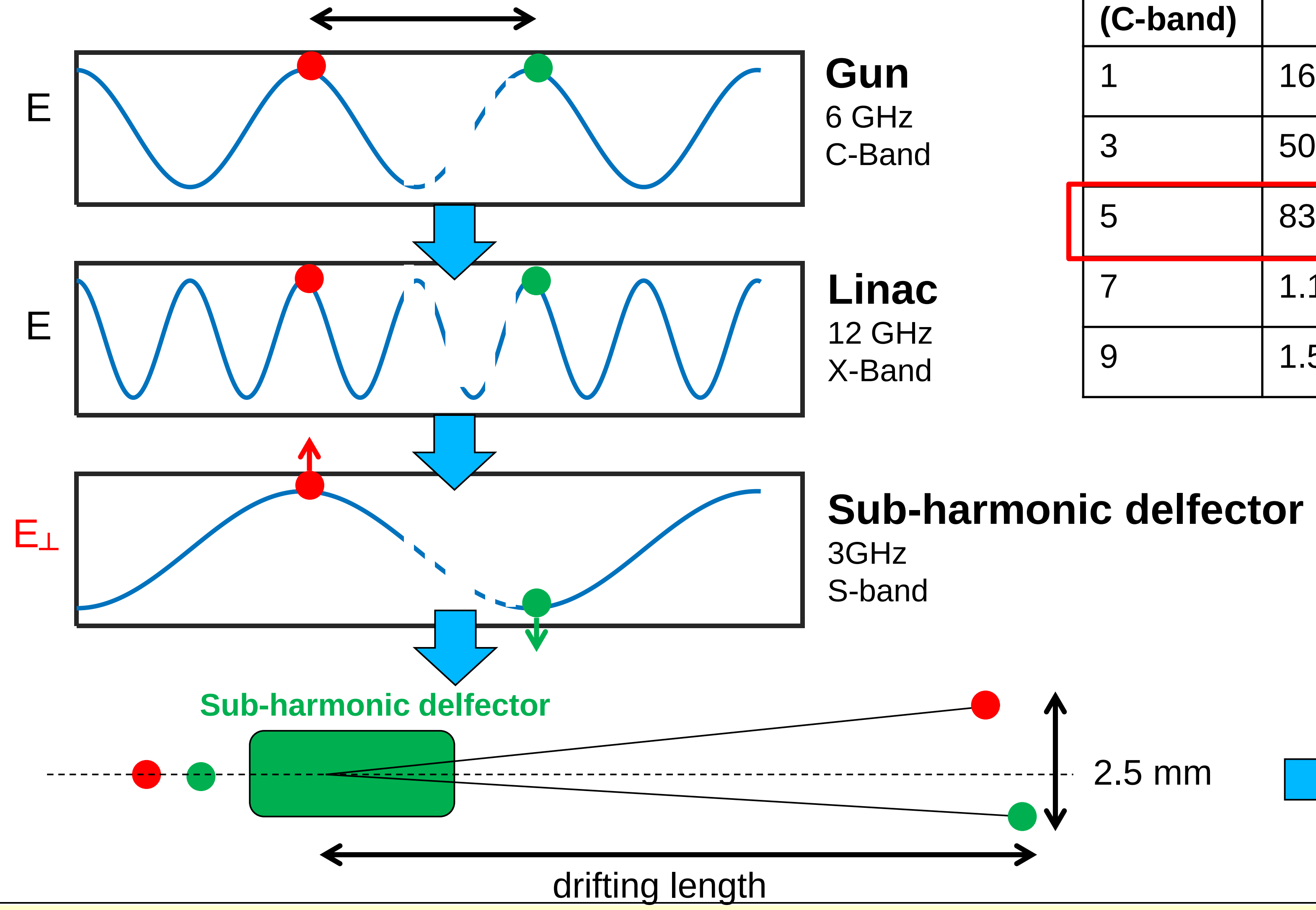
Sub-harmonic delfector and spacing between two bunches

$\Delta t = n\, \tau_{gun}$, $n = 1,3,5...$

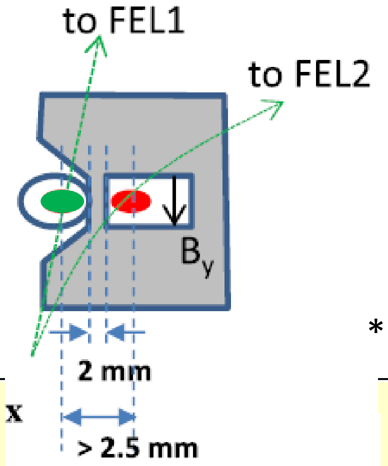
$\Delta s = n\, \lambda_{gun}$



n (C-band)	Δt	Δs
1	166 ps	50 mm
3	500 ps	150 mm
5	833 ps	250 mm
7	1.16 ns	350 mm
9	1.5 ns	450 mm

n (X-band)	n (S-band)
2	0.5
6	1.5
10	2.5
14	3.5
18	4.5

Spacing between the two bunches is 10 X-band rf cycles



* Courtesy by N. Thompson

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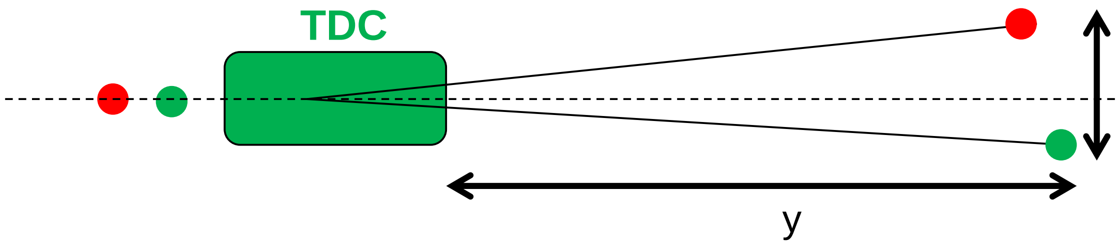
Transverse deflector system design

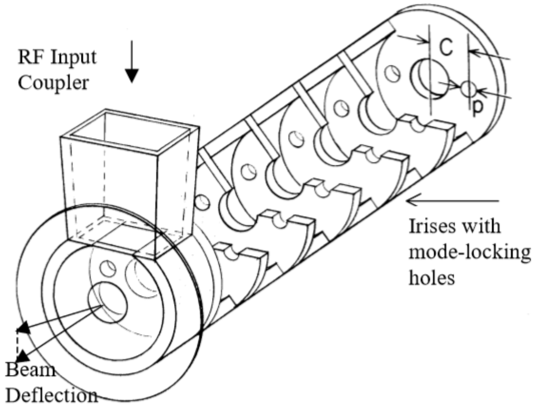
HXR mode: 5.5 GeV bunch
x=2.5 mm, y is drift length

$$\frac{V_\perp e}{E} = \frac{x/2}{y}$$

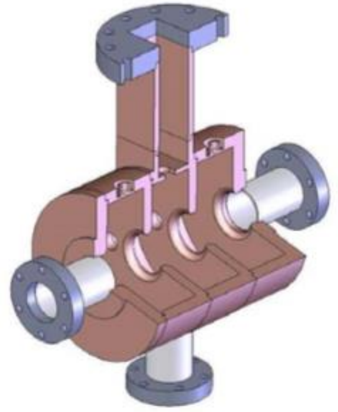


Two options for the transverse deflecting cavity
1. Traveling-wave structure
2. Standing-wave structure

Traveling-wave structure



Standing-wave structure



RF parameters

2998 MHz	Traveling-wave ($2\pi/3$)	Standing-wave
Cell number	N	3
Single cell length [m]	0.033	0.05
Structure length [m]	N*0.033	0.15
Shunt impedance [MΩ/m]	20.25	21.11

Power capability

Klystron: based on VKS8262G1 model built by CPI
Maximum rf peak power of 7.5 MW→6 MW within loss@1000 Hz
Pulse length of up to 5 μs
Repetition rate of 400 Hz

Pulse compressor: spherical pulse compressor
Increase the average power:
6 MW, 4.5 us →31.7 MW, 300 ns (Avg.)

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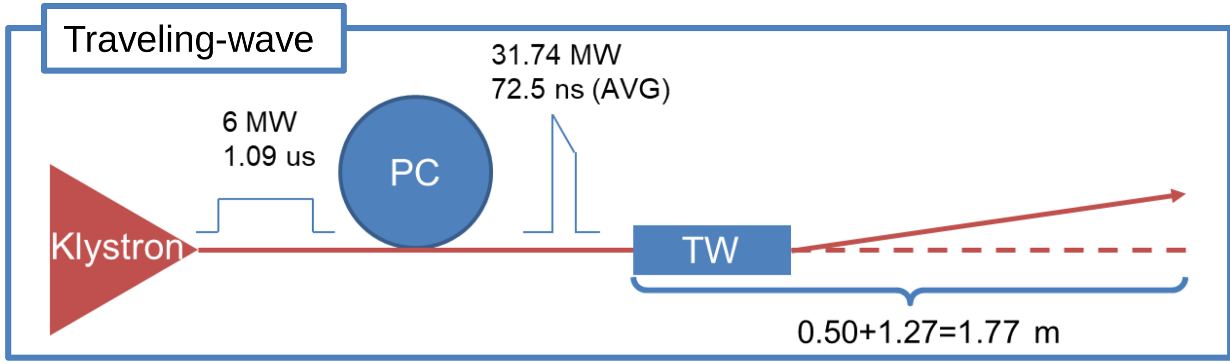
Transverse deflector system design

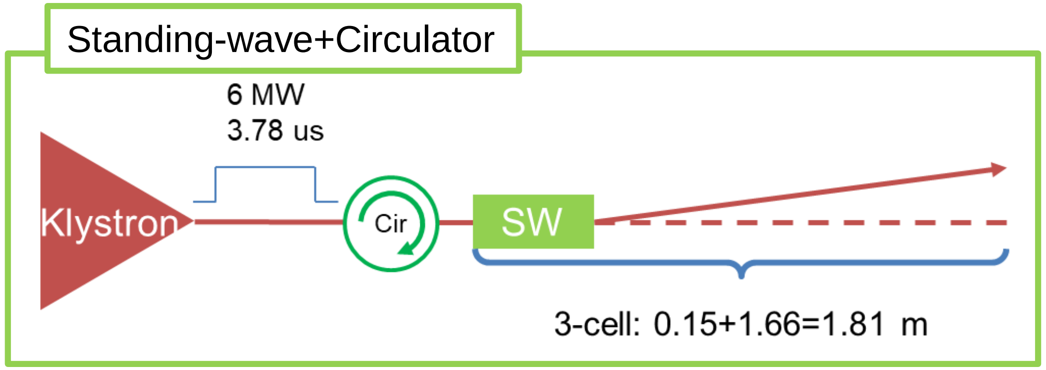
6 MW @ 1000 Hz from the power source

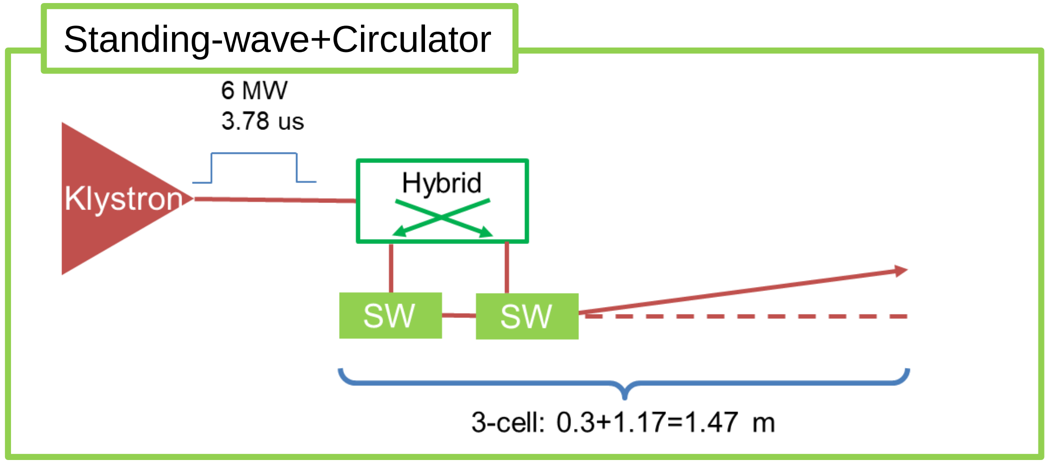
1. Klystron, pulse compressor, 0.5 m traveling-wave structure

2. Klystron, circulator/hybrid, 0.15 m standing-wave structure

	Stru. length [m]	Drift length [m]	Deflecting voltage [MV]
Traveling-wave	0.5	1.27	5.4
Standing-wave	0.15	1.66	4.15
2* SW +Hybrid	0.15	1.17	5.87







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PolariX TDS

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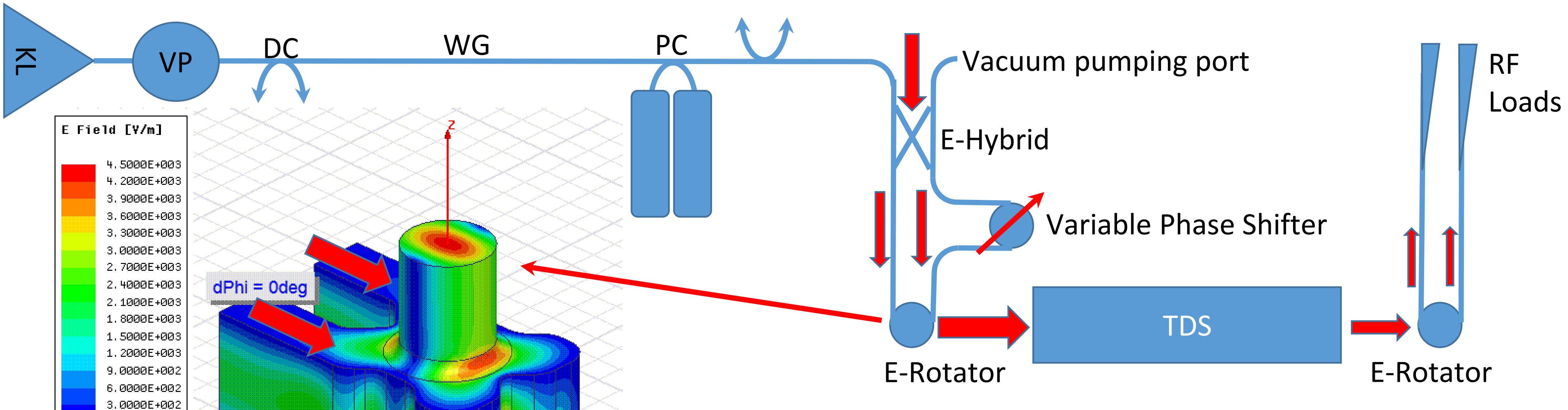
* Courtesy by A. Cianchi and A. Grudiev

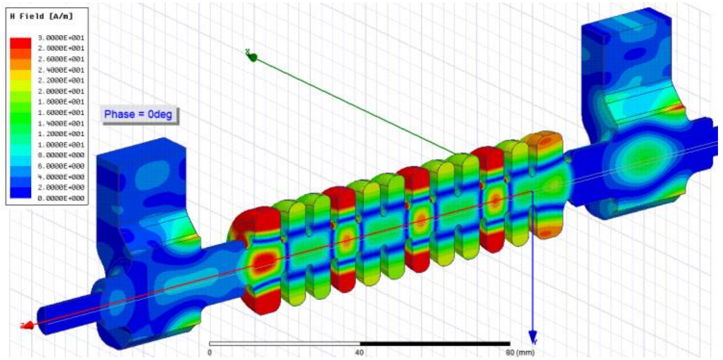
PolariX TDS is a variable Polarization X-band Transverse Deflecting Structure
For longitudinal phase space characterization in CompactLight



A. Grudiev, CLIC-note-1067 (2016).

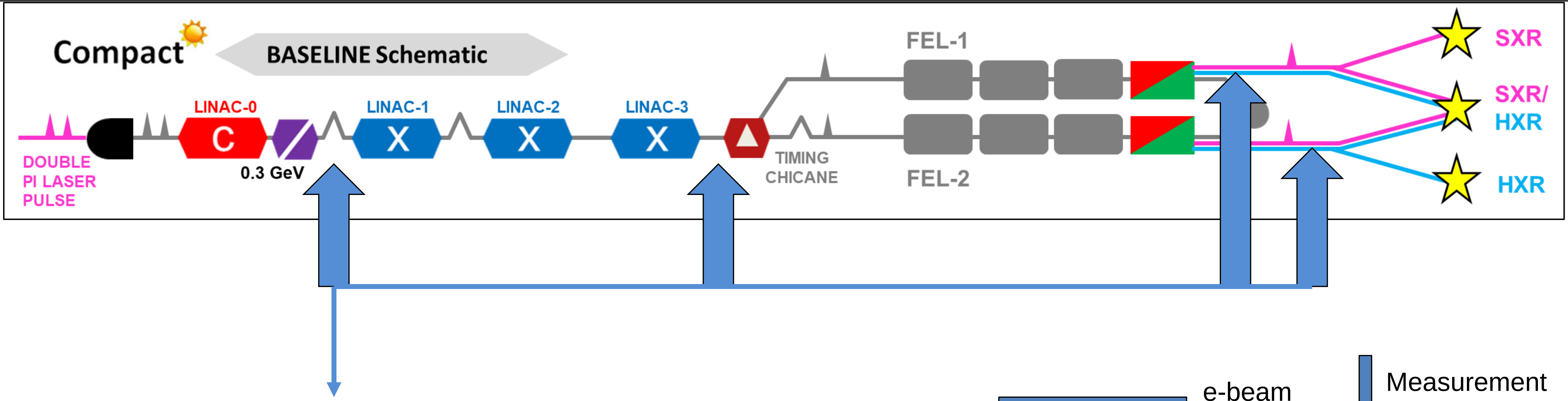
Phase difference between port 1 and port 2:

- 0 degree -> vertical polarization
- 180 degree -> horizontal polarization

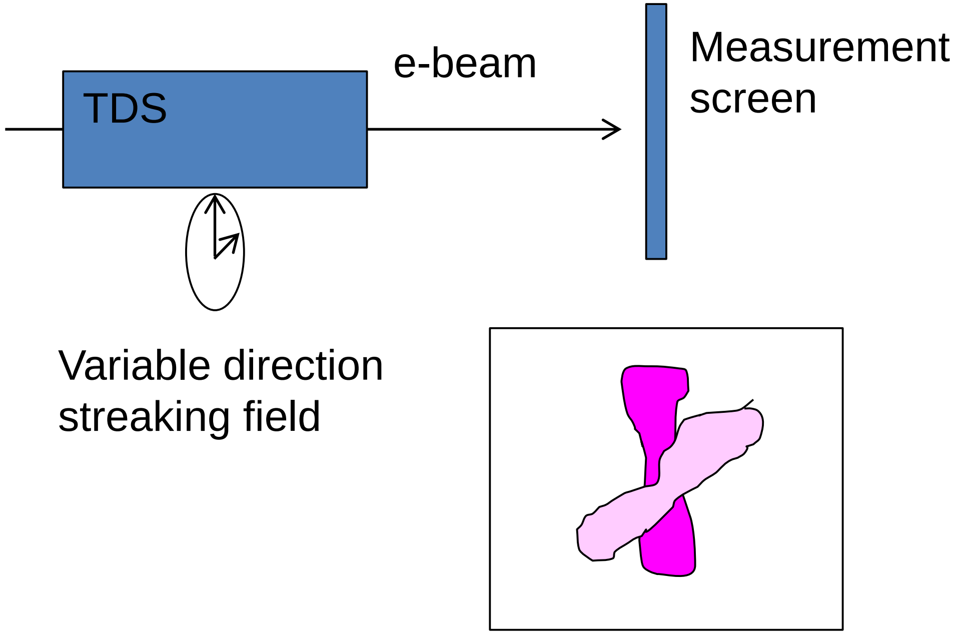


https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.23.112001

PolariX TDS in CompactLight



4 PolariX TDS in total:
1 TDS after bunch compressor 1 to measure the phase space at low energy
1 TDS before the FEL lines to measure the phase space entering the undulators
2 TDS after the two FEL lines to control the lasing inside the undulators



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Summary

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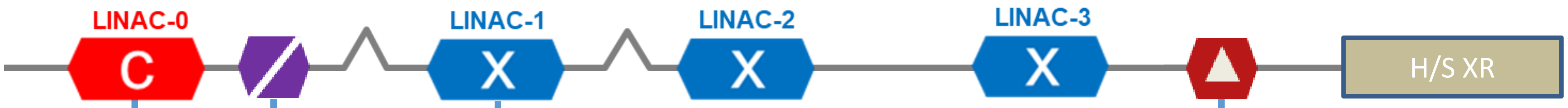

C-band rf system: RF gun and injector

Diagnostics system: PolariX TDS

Ka-band rf system: Harmonic linearising structure

X-band rf system: Main linac structure design

S-band rf system: Sub-harmonic transverse deflector system design

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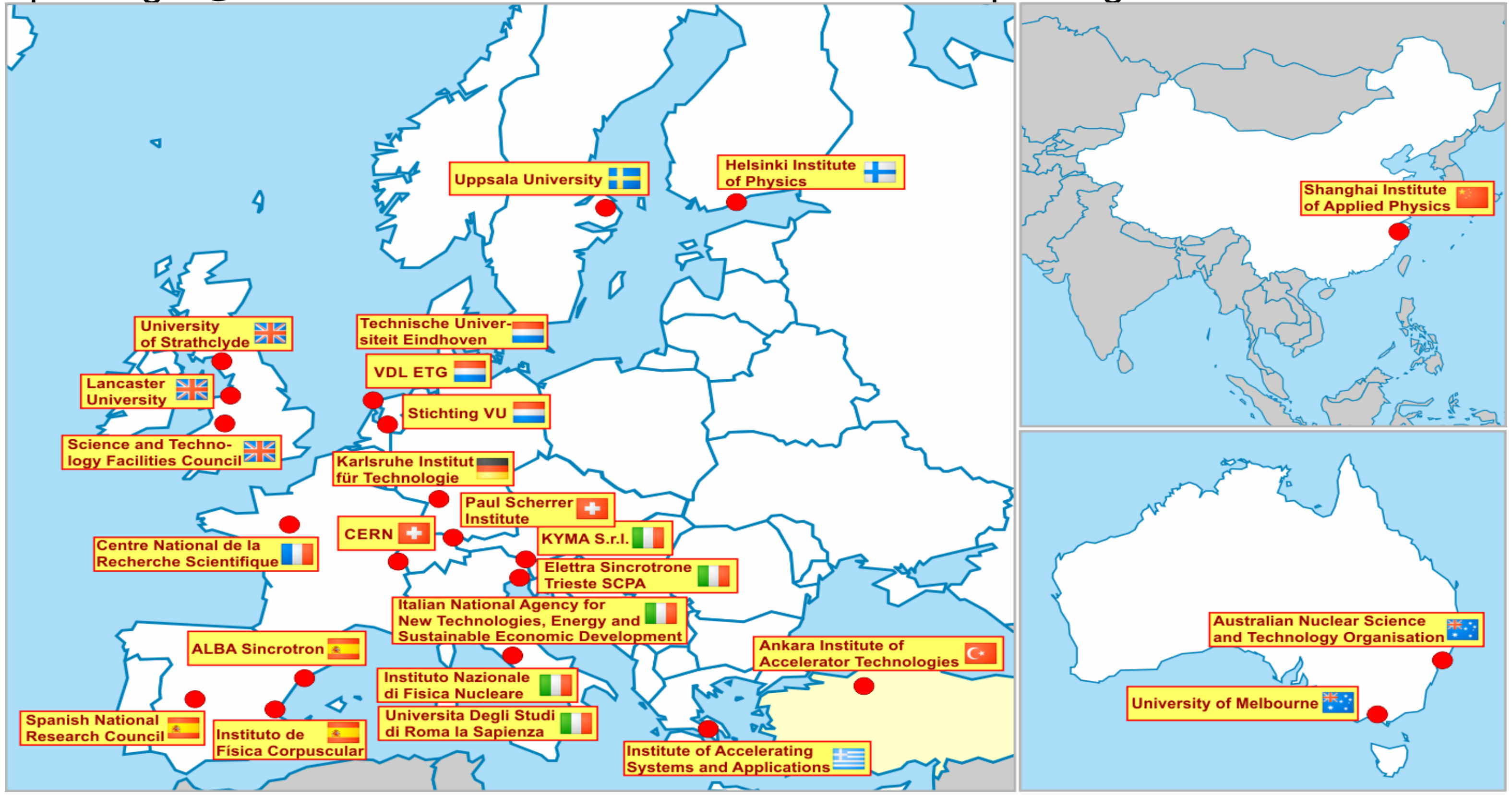
Thank you!

CompactLight@elettra.eu   www.CompactLight.eu



CompactLight is funded by the European Union's Horizon2020 research and innovation programme under Grant Agreement No. 777431.

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Linac layout

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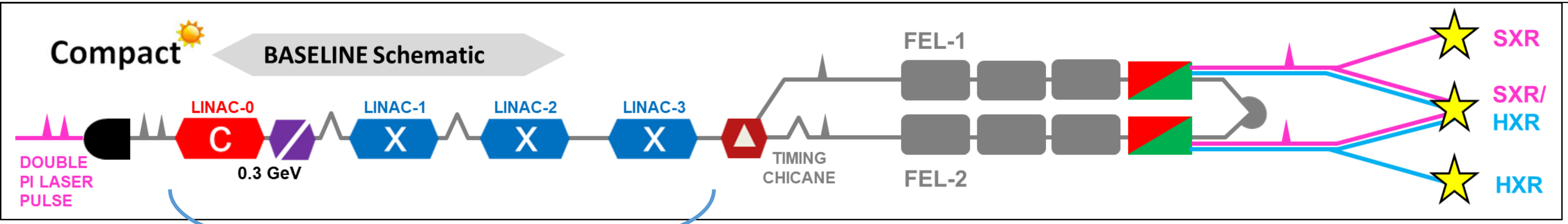

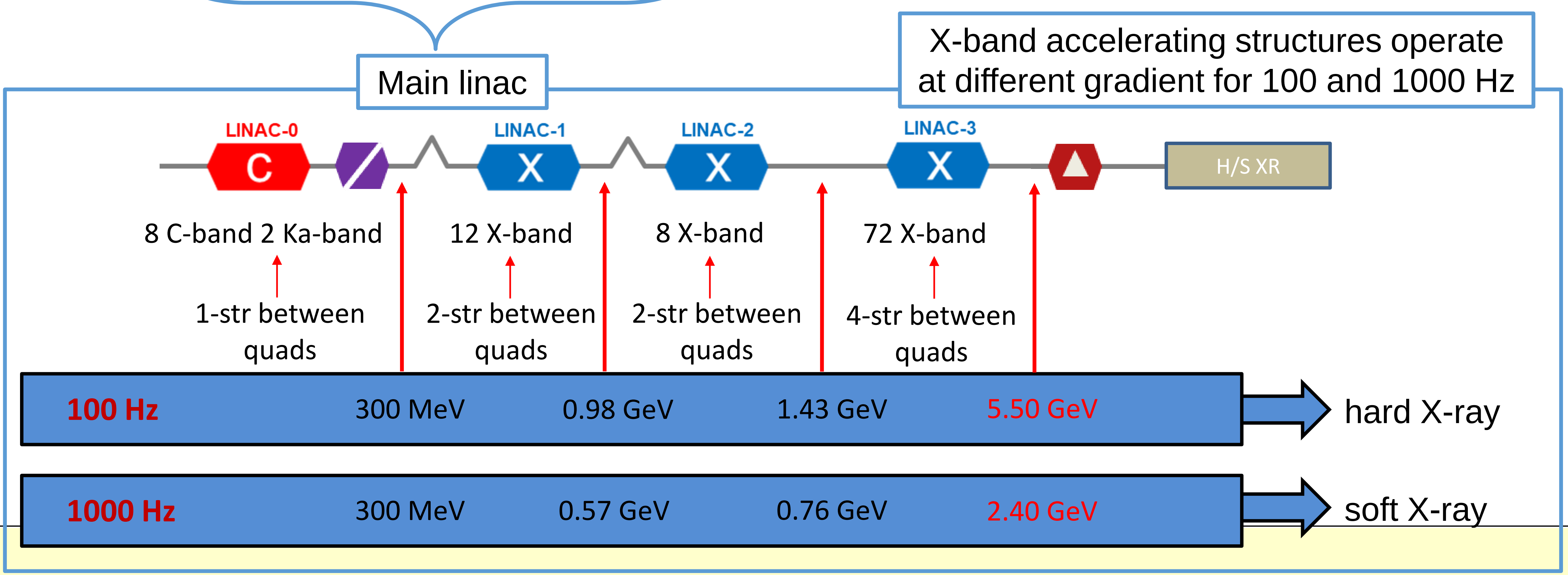

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Main Electron Beam Parameters

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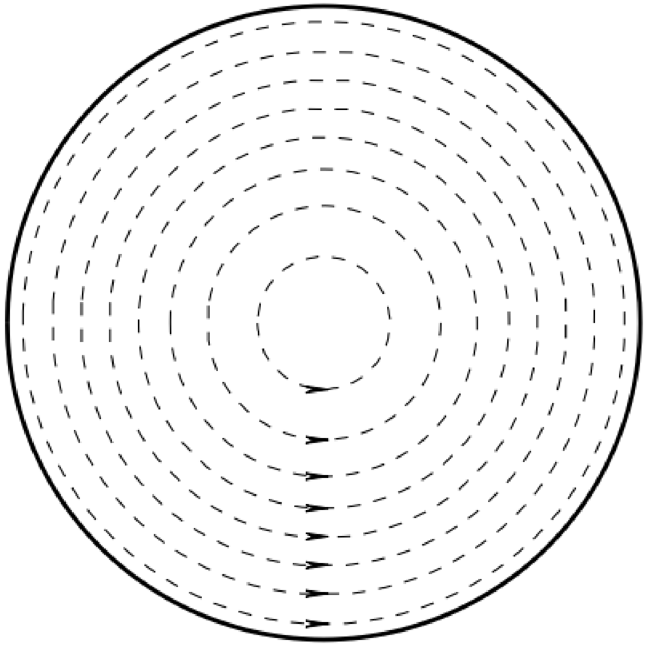
Parameter	Unit	HXR	SXR	SXR	SXR
Rep Rate		100 Hz		250 Hz	1000Hz
Beam Energy	GeV	2.75-5.5	1-2	1-2.5	1-2
Bunch Charge	pC	75		75	75
Number of bunch per RF pulse	#	1-2		1-2	1-2
RMS Slice Energy Spread	%	0.01	0.02	0.02	0.02
Minimum Electron bunch length rms	fs	15	30?	30	30
Peak Current	kA	5	1	1	1
Normalised Emittance	mm-mrad	0.2	0.2	0.2	0.2

When we operate low rep-rate bunch length will be defined by HXR requirement
The second bunch going to SXR BL will have same bunch length

TM110 mode in transverse deflecting cavity

Transverse magnetic field of TM010 and TM110 in pillbox cavity

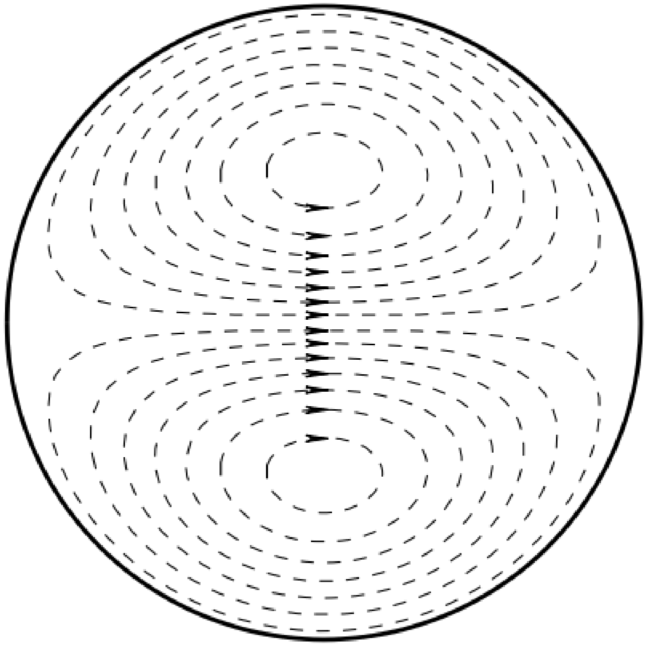
TM010 mode



Accelerating mode

$$\frac{f_{TM_{110}}}{f_{TM_{010}}} = 1.59$$

TM110 mode



Dipole mode
Transverse kick to beam

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Transverse deflecting cavity (TDC) design

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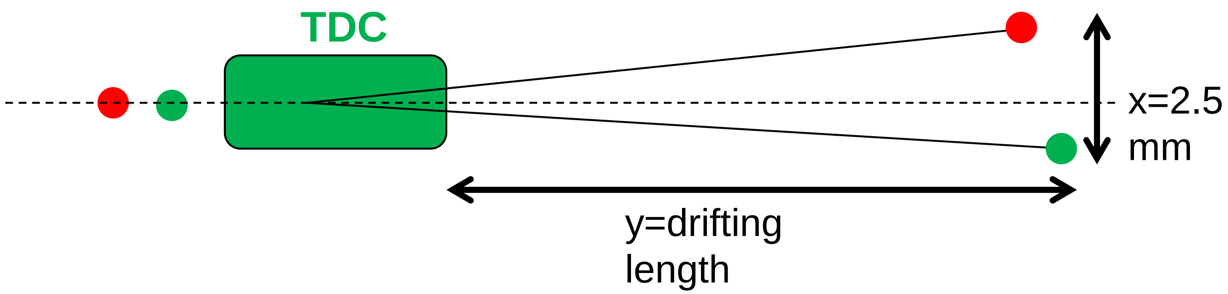
Hard X-ray mode: 5.5 GeV bunch
x=2.5 mm, y is drift length

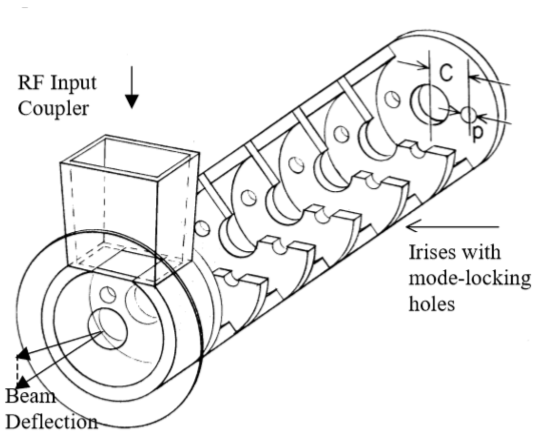
$$\frac{V_{\perp} e}{E} = \frac{x/2}{y}$$



Voltage of deflector could be reduced if we increase the drift length
Longer drift length makes standing-wave deflecting cavity possible

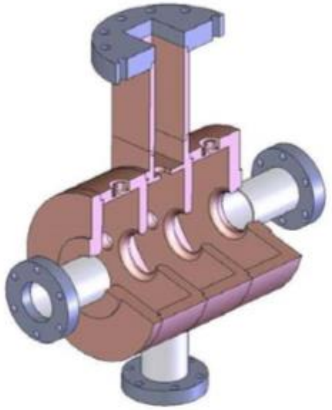
Two options for the transverse deflecting cavity
1. Traveling-wave structure
2. Standing-wave structure, 3-cell structures

Traveling-wave structure



SLAC type LOLA TDC
TM110, $2\pi/3$ mode
Length=2.4 m
Filling time~ 300 ns

Standing-wave structure



Tsinghua University type 3-cell structure

INFN type 5-cell structure

Loew, G. A., & Altenmueller, O. H. DESIGN AND APPLICATIONS OF RF DEFLECTING STRUCTURES AT SLAC. 1965
Shi, J. phD thesis. 2009
Alesini, D., et al. RF deflector design and measurements for the longitudinal and transverse phase space characterization at SPARC. Nucl. Instrum. Methods Phys. Res. A, 568(2), 488-502. 2006

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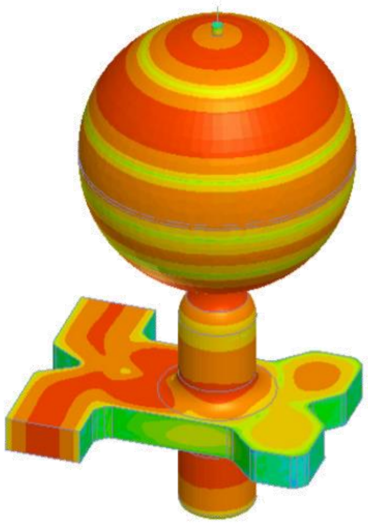
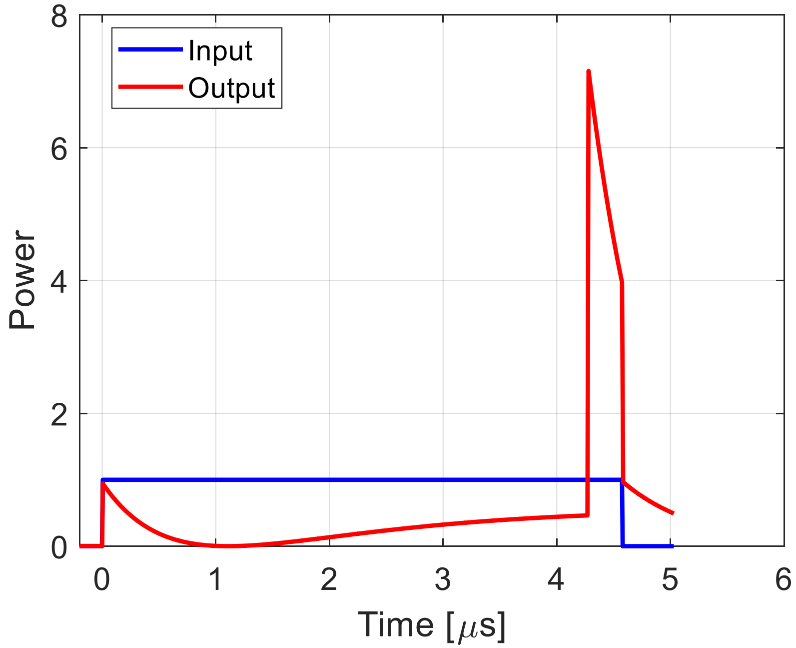
Power capability

CPI S-band Klystron (VKS8262G1):
7.5 MW, 5.0 μs, 400 Hz flat pulse
already applied in IFIC S-band test-stand in Valencia

With spherical pulse compressor:
39.7 MW, 300 ns (Avg. without loss) compressed pulse





Spherical pulse compressor	
frequency	2.998 GHz
Q_0	100000
Coupling factor	7
Compression ratio	15
Peak power gain	7.15
Average power gain	5.29

Esperante Pereira, Daniel, et al. "Construction and Commissioning of the S-Band High-Gradient RF Laboratory at IFIC." J. Phys. Conf. Ser.. Vol. 1067. 2018.

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Traveling-wave transverse deflecting structure design

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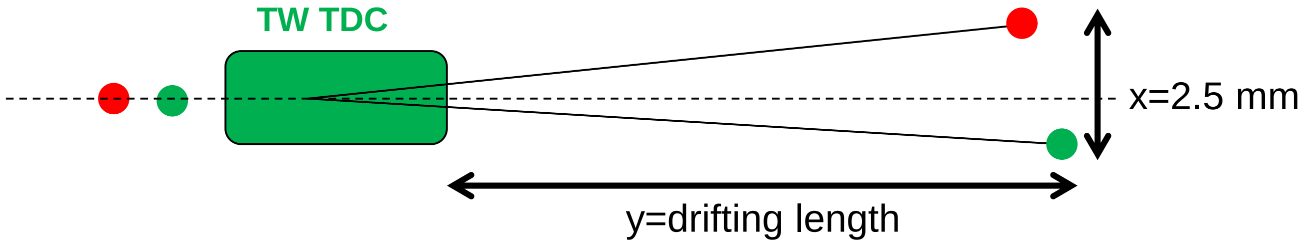
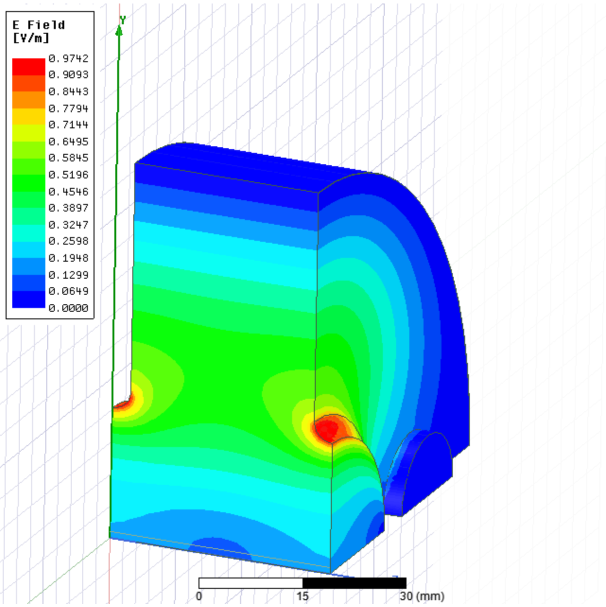
Increasing the drift length can reduce the length of traveling-wave structure

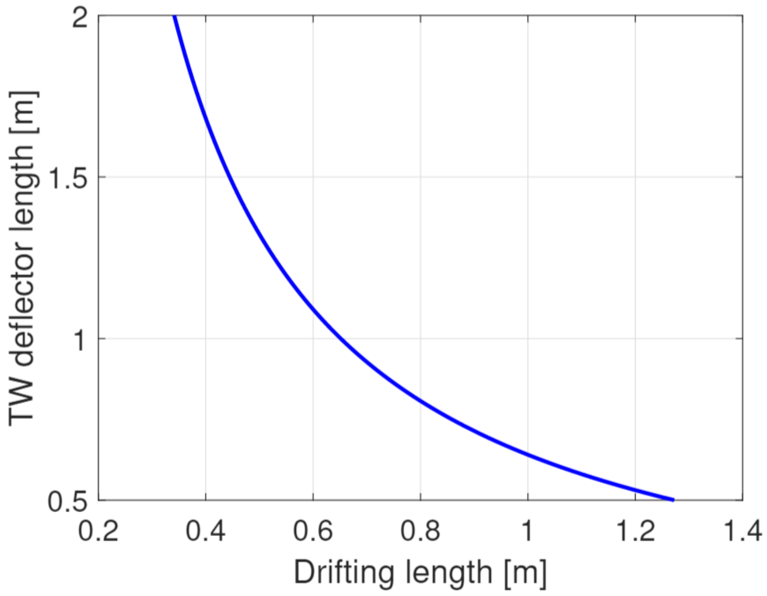
Work at $2\pi/3$ mode

0.5 m TW structure (filling time 62.5 ns)
6 MW 1.09 μs klystron pulse
31.74 MW 72.5 ns compressed pulse





Freq [GHz]	2.998
R [MΩ/m]	20.25
Q	12369
v_g/c [%]	2.7



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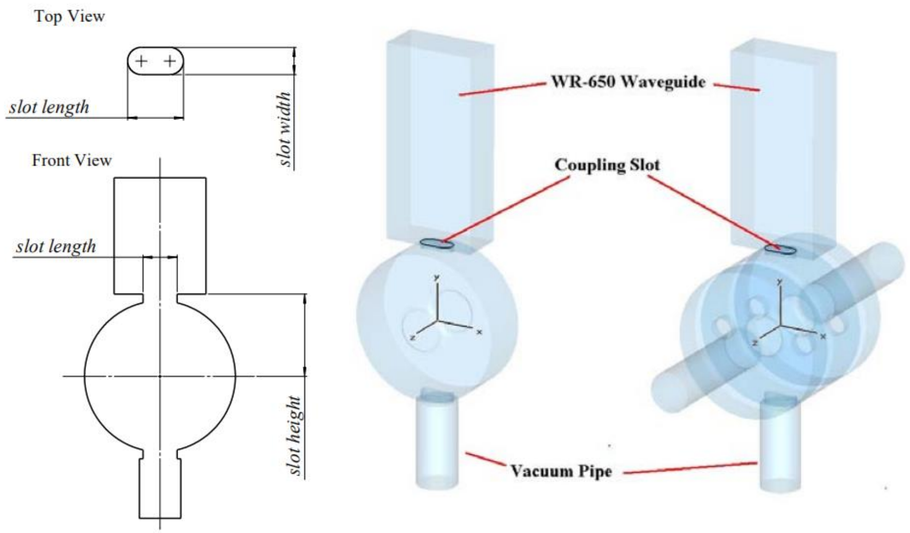
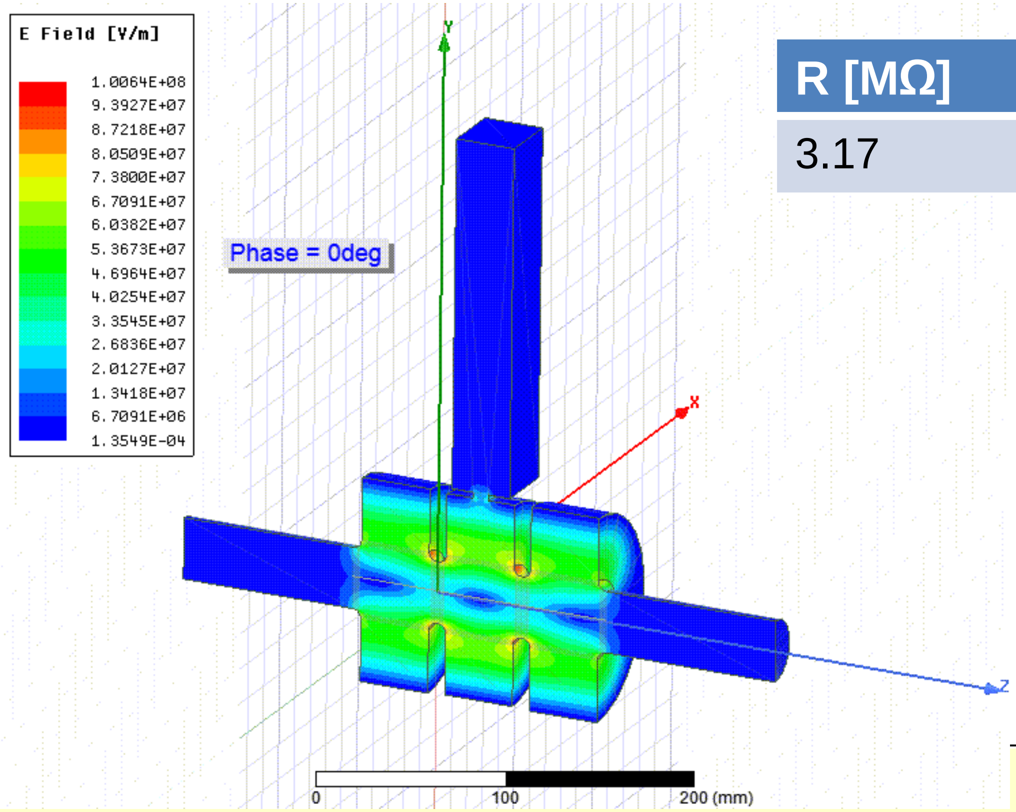
3-cell standing-wave transverse deflecting structure design



Use race track shape coupling hole
4.15 MV deflecting voltage @ 6 MW input power
Maximum surface field around 100 MV/m

Filling time $(2 * Q_l/\omega)$ ~ 820 ns
Time to fill 99% E field ~ 3776 ns



R [MΩ]	Freq [GHz]	Q
3.17	2.998	15642