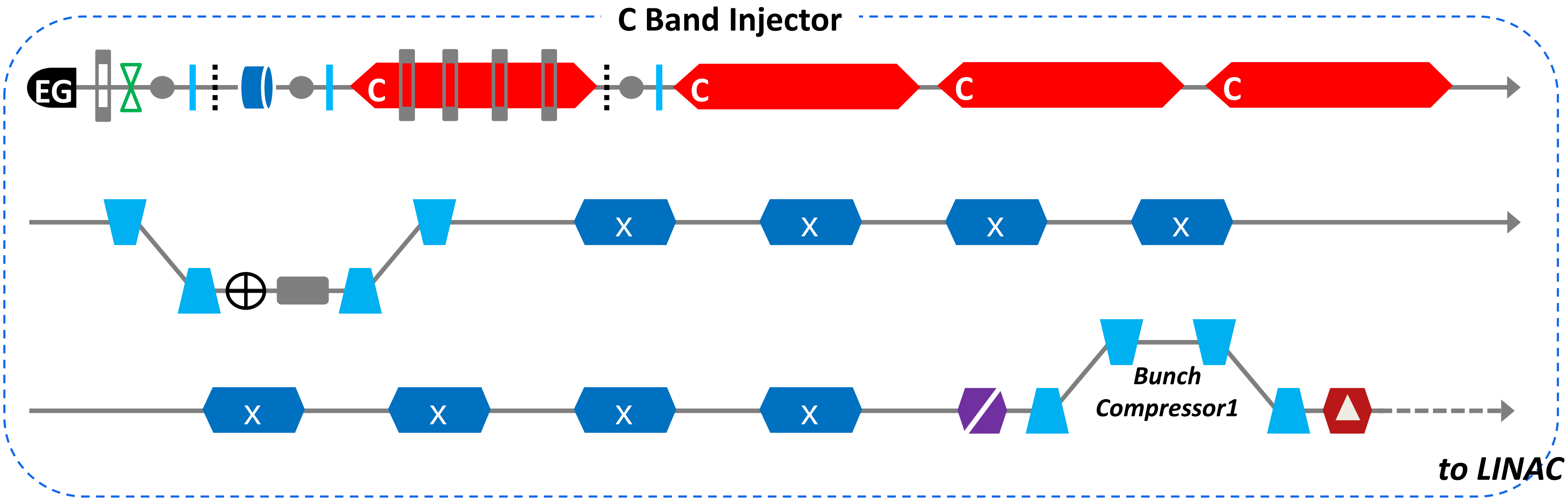
D3.4: Design of the CompactLight e-gun and injector, with phase space linearizer

Massimo.Ferrario@lnf.infn.it



WP3 Deliverables

- **D3.1** - Preliminary assessments and evaluations of the optimum e-gun and injector solution for the CompactLight design, **(=>M18)**.

- **D3.2** – A review report on the bunch compression techniques and phase space linearization, (**=>M18**).

- **D3.3** – Design of the injector diagnostics/beam manipulations based on a X-band cavities (**=>M39 => Cianchi+Mostacci**).

- **D3.4** - Design of the CompactLight e-gun and injector, with phase space linearizer (**=>M39 => Ferrario**).

- **→ WP3 CDR Contribution**

D3.4 Abstract

In this deliverable we report the design of the high brightness, high repetition rate injector suitable to match the CompacLight X-band linac requirements.

Different schemes have been investigated including RF gun injectors at different operating frequency (S, C and X band) and a DC gun based design. After a careful comparison among the possible options the preferred choice has been identified on the C-band photo-injector followed by and X-ban Booster up to the first Bunch Compressor (BC1) at about 300 MeV. The injector is also equipped with a Laser Heater at low energy and a Ka-band linearizer before the BC1.

This configuration allows the operation at high repetition rate (~1kHz) while keeping high quality bunch performance. Moreover with the same configuration is possible to drive independently both high and low repetition rate as needed for the soft and the hard x-ray FEL undulators.

The details of the layout are discussed in this deliverable. In the Appendix the advancement of the other options are also reported.

D3.4: Design of the CompactLight e-gun and injector, with phase space linearizer

Tentative Index and Load distribution:

a) Introduction (Ferrario) => Ref. D3.x
b) Start to End Simulations (Giribono, Vaccarezza, Scifo) => Ref. D6.x
c) Injector CAD model (Gazis)
d) Laser and Photocathode systems (Scifo)
e) 2.5 cells C-band RF gun and Solenoid design (Alesini)
f) C-band booster (Alesini)
g) Laser Heater design (Di Mitri)
h) X-band booster (Alesini, Gallo, Wuensh) => Ref. D4.x
i) Ka-band Linearizer (Burt) => Ref. D4.x
j) BC1 (Vaccarezza)
k) Appendix: any other contribution (All)

Activity carried out in Task 3.1.

The baseline injector design (described in detail in Deliverable D3.4) has been achieved by comparing several different schemes and alternative configurations supported by simulation results. The final layout has been worked out after a deep investigation of all possible alternatives and the optimized configuration is the results of several iterations as described hereafter.

-*In November 2019* we have organized a mini-workshop in Frascati aiming to compare simulations of the different Gun options in terms of achievable beam quality, capability to operate up to 1 kHz repetition rate and expected technical readiness level on a time scale of the next 5 years. At the end of the mini-workshop we all agreed to consider as the main reference a 1.6 cells C-Band RF Gun (option 3.1b) followed by a C-Band Booster up to at least 150 MeV.

-*In January 2020,* during the XLS Meeting in Athens, we have decided using the same injector layout for both the operational modes, high (1kHz) and low (100 Hz) repetition rate, that implies operating the whole injector at a moderate accelerating gradient while keeping the beam quality within the requirements. This choice allows saving the costs of a double injector scheme with a dedicated injector for each operational mode.

-*In June 2020,* during the XLS Glasgow Virtual Meeting, we have decided to increase the beam energy at the C-Band RF Gun exit (from 4 to 6 MeV) by adding one more cell to the Gun: from 1.6 to 2.6 cells. This choice was driven by a request from WP8 (Diagnostics) in order to ease the accommodation of all the required diagnostics tools downstream the Gun.

-*In October 2020,* during a dedicated virtual WP3 meeting, we fixed the baseline injector layout up to 300 MeV that now includes, downstream the C-band injector, a Laser Heater (option 3.2d), a second X-band booster up to 300 MeV, a K-Band Linearizer (option 3.4b) and a Magnetic Compressor BC1 (option 3.2d). This configuration meets the design goals of the XLS injector. A Copper Cathode driven by a 1 kHz Ti:Sa Laser results to be proper choice for the electron source.

-*Finally, in December 2020* during a dedicate WP3+WP4+WP6 meeting, has been suggested to investigate a possible operation in a hybrid compression mode, i.e. with a combination of BC1 and Velocity Bunching (option 3.2b). This possible upgrade is still under study and, if successful, it might be included in the final XLS Conceptual Design Report.

Participants: the involved partners in this Task have been INFN (P13), CERN (P2), IASA (P5), UA-IAT (P9), TU/e (P12), ALBA-CELLS (P17), CNRS (P18), CSIC-IFIC (P21), UniTov (P25).

Injector Layout Evolution

(After interactions among WP3-WP4-WP6-WP8)

1) November 2019, Frascati WP3+WP6+WP2 joint meeting “XLS Injector road-map“:

- ➔ **It was decided to use a C-band photo-injector**
- ➔ Any other option will be included in the TDR in the Appendix

2) January 2020, “Athens annual meeting”, (presented by M. Croia):

- ➔ First S2E: C-band gun + Ka-band + C-band TW + Ka-band
- ➔ **It was decided to use the same photo-injector for both LRR and HRR operational modes**

3) June 2020, Glasgow virtual meeting,(presented by A. Giribono):

- ➔ C-band gun + 10 C-band TW + Ka-band (no velocity buncher)
- ➔ **It was decided to use a 2.5 cells gun and a longer downstream drift**

4) October 2020, Injector meeting, (presented by C. Vaccarezza):

➔**S2E for 2.5 C-band gun + 4 C-band TW + Laser Heater + 8 X-band TW + Ka-band (no velocity buncher) (BASELINE DESIGN FOR D3.4)**

- ➔ It was decided to check possible Velocity Bunching operation

5) December 2020, (presented by J. Scifo):

➔ S2E for 2.5 C-band gun + Ka-band+ 4 C-band TWS + 8 X-band TWS + Ka-band (with Velocity Buncher) (**in progress for the TDR if successful)**

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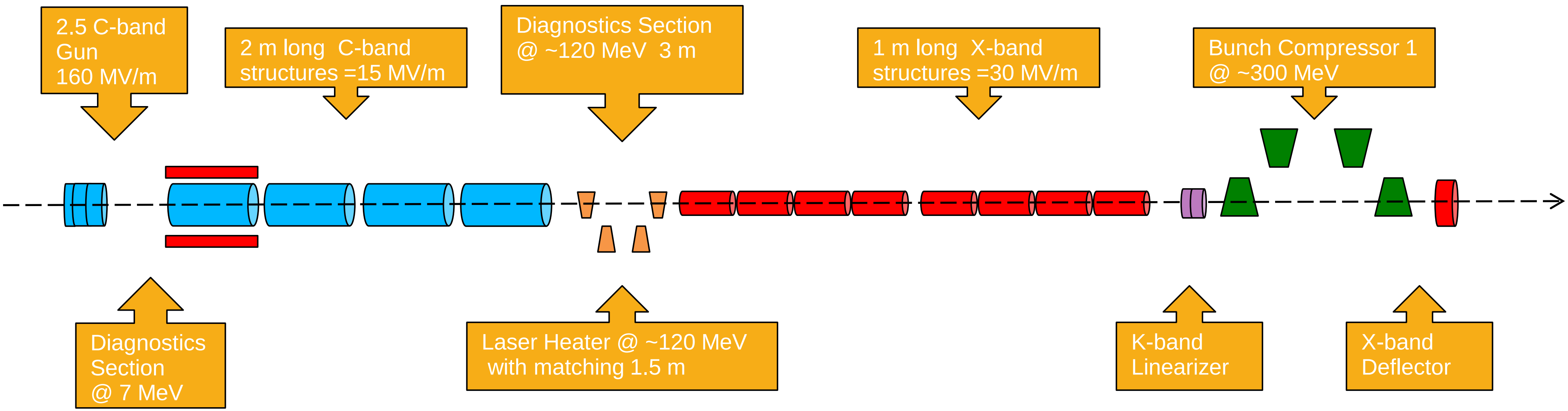
XLS Injector Reference Base-Line

Compact

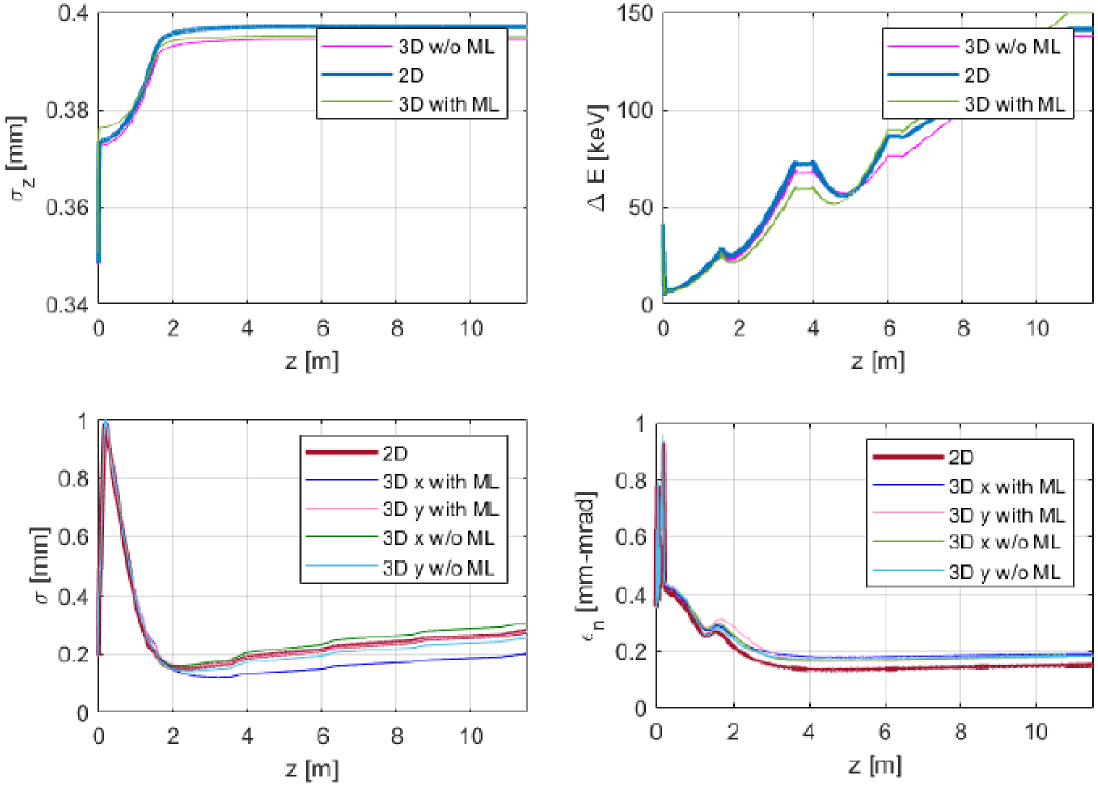
- One injector for both operational modes (HRR and LRR)
  - 2.5 C-band gun with 160 MV/m cathode peak field => longer drift for diagnostics
  - Copper cathode and TiSa Laser
  - Same gradients 15/30 MV/m in C/X-band structures
  - Same diagnostics positions (@ gun exit 7 MeV and in the drift parallel to the LH @ 120 MeV)
  - Same beam parameters at the linac exit
  - Solenoid around first C-band accelerating structure, allows also possible VB operation



- BC1 system includes:
  - Laser Heater @~120 MeV
  - K-band Linearizer just before the BC1, X-band RFD downstream BC1
  - Same beam parameters at the BC1 exit

Beam dynamics simulations – Gun with mode launcher

- A *cylindrical symmetric gun with coaxial mode launcher is described by a 3D field map*



Field tails of the mode launcher for the C-band gun don't affect the beam quality

Next step would be considering various configurations for the mode launcher

		6 C-band 15 MV/m (1 kHz)	8 X-Band 32 MV/m (1 kHz)
Effective Accelerating Length	$L_{acc}^{eff}\ (m)$	11.4	7.2
Current	$I(A)$	300	300
Bunch length rms BC1 exit	$\sigma_z\ (\mu m)$	26	19
Slice Hor Norm Emittance	$\varepsilon_{nx}\ (\mu m)$	< 0.1	~ 0.1
Energy before BC1	$E(MeV)$	275	323

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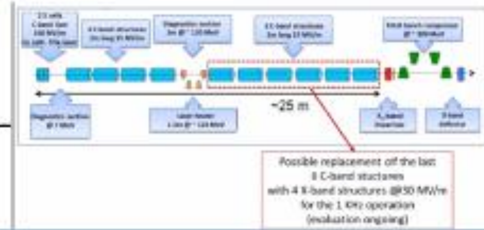
3. Injector 3D CAD



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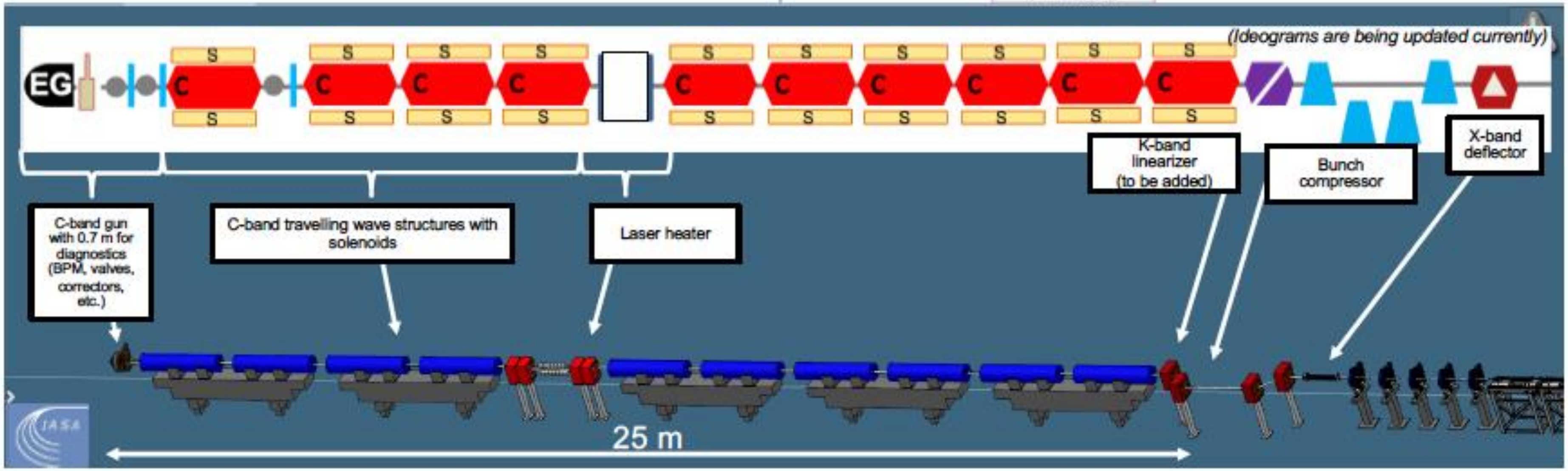
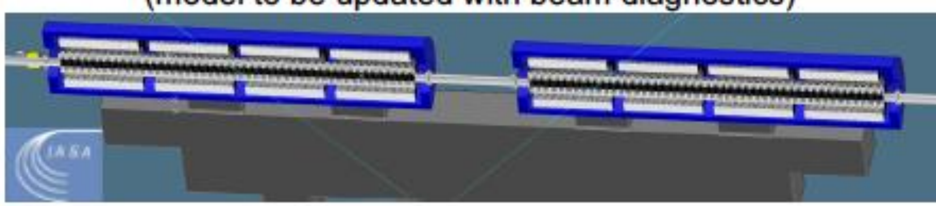
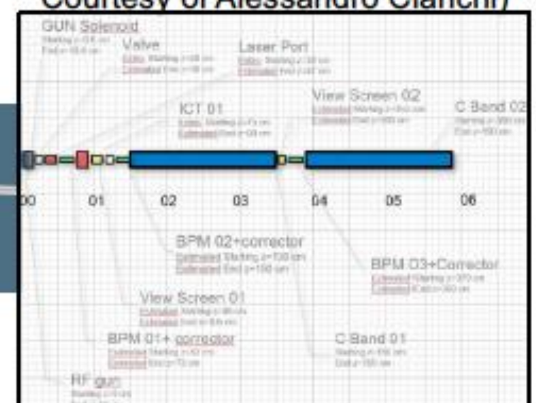


2.5 cell C-band gun with bucking coil and Cu cathode plug (gun design by INFN)

C-band travelling wave structures with the corresponding solenoids (model to be updated with beam diagnostics)



Beam Diagnostics (updates to be implemented) Courtesy of Alessandro Cianchi)



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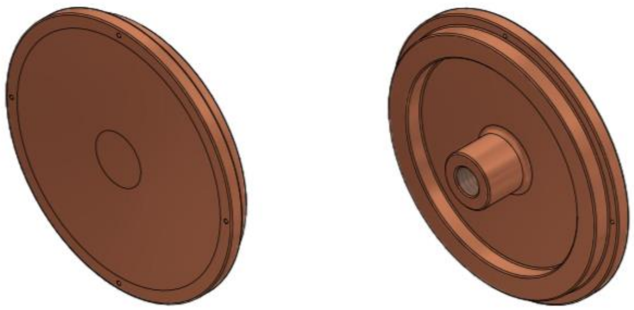
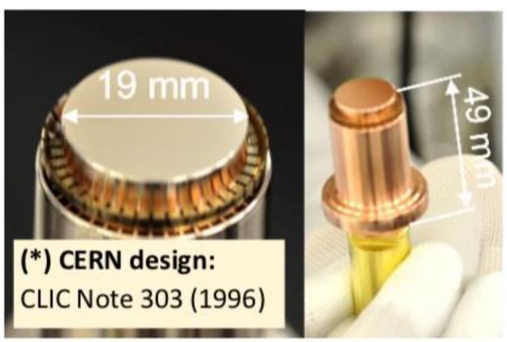
Compact

Laser and Photocathode systems



Cu flange- SPARC_LAB like

or



Exchangeable cathode plug *

Cu plug for Load lock system- CLIC/PSI like

Specifications

ARCO C (100 Hz) & ARCO M (1 kHz)

Specifications			
Repetition Rate [1]	100 Hz for Arco C	1 kHz for Arco M	
Energy Per Pulse [2,3]	6 mJ @ 100 Hz / 5 mJ @ 1 kHz	12 mJ @ 100 Hz / 10 mJ @ 1 kHz	25 mJ @ 100 Hz / 20 mJ @ 1 kHz
Pulse Width (fwhm) [4]	< 100 fs or < 35 fs or < 20 fs		
Central Wavelength (nm) [5]	800 ± 10		
Average Power (W)	5	10	20
Pump Lasers	Terra	Terra Duo	2 Terra Duo
Pulse To Pulse Energy Stability (RMS)[6]	0,7 %	0,7 %	0,5 %
Power Stability (RMS) [7]	1 %		
Nanosecond Contrast [8]	< 5.10^{-4}		
Picosecond Contrast [9]	< 5 10^{-7} @ 300 - 50 ps & < 10^{-6} @ 50 - 10 ps & < 10^{-5} @ 1 ps		
Beam Quality M²	< 1.3		
Pointing Stability	< 10 µrad RMS		
Polarization	Linear horizontal		
Warm-up Time	< 1 hour		

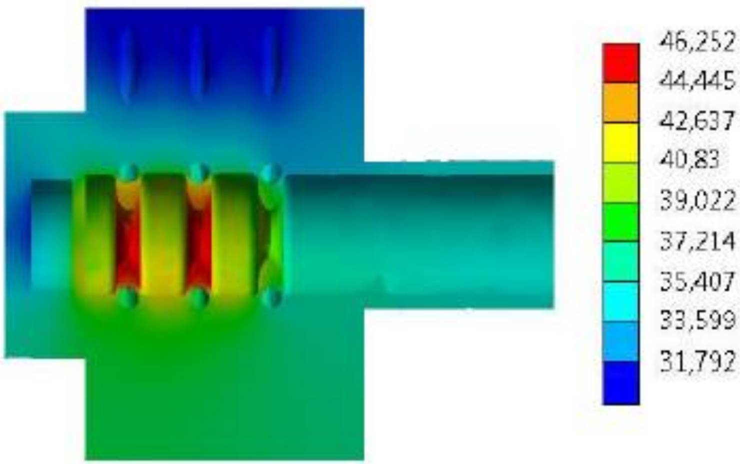
[1] Please contact factory for specifications at other repetition rates
[2] 5 mJ / 9 mJ / 20 mJ @ 100 Hz or 4 mJ / 9 mJ / 16 mJ @ 1 kHz for pulse duration < 25 fs
[3] 790 nm +/- 10 nm for 100 fs pulse duration. Other central wavelengths, please contact factory
[4] Factory-set, must be specified when ordered and will be optimized prior to shipment
[5] Over 2000 pulses
[6] Over 8 hours under stable environmental conditions
[7] Pre-pulse, regenerative amplifier replicas
[8] Measured with third order cross-correlator (SEQUOIA)

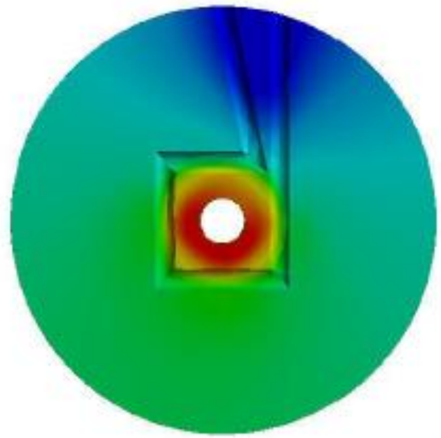
Ti-Sa Laser (SPARC_LAB like but by using higher Repetition Rates)
https://amplitude-laser.com/frequence/khz-en/
Possible Issue: Optical transport components damages

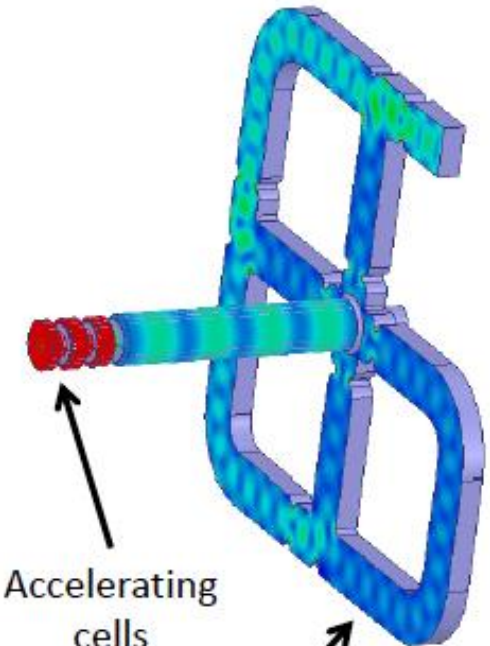
GUN DESIGN: E.M. AND THERMO-MECHANICAL

Compact

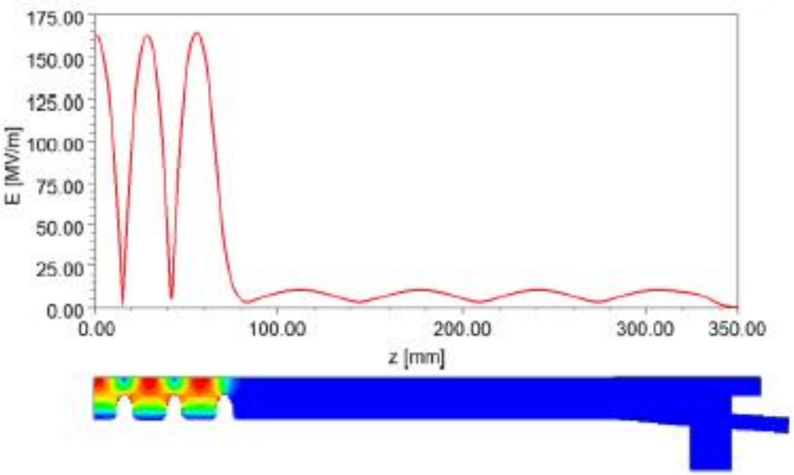
- ⇒ The e.m. design has been done using **Superfish and ANSYS Electronics.**
- ⇒ Scaling of the 4-ports mode launcher still in progress.
- ⇒ A **complete thermo-mechanical analysis** has been done for the 1 kHz operation using ANSYS workbench (L. Pellegrino, A. Gizzi)
- ⇒ **Solenoid** preliminary design done with Poisson (solenoid + bucking coil)

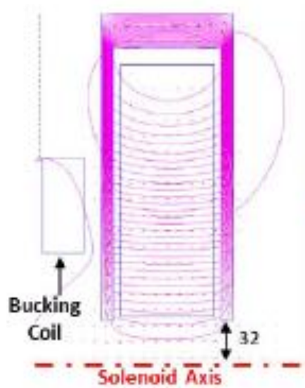


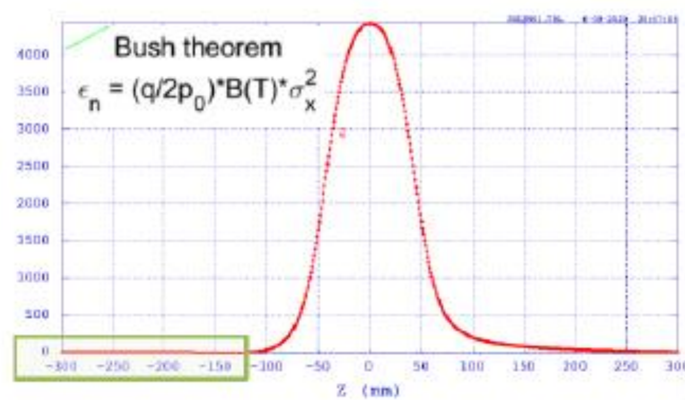




G Castorina et al 2018 J. Phys.: Conf. Ser.1067 082025

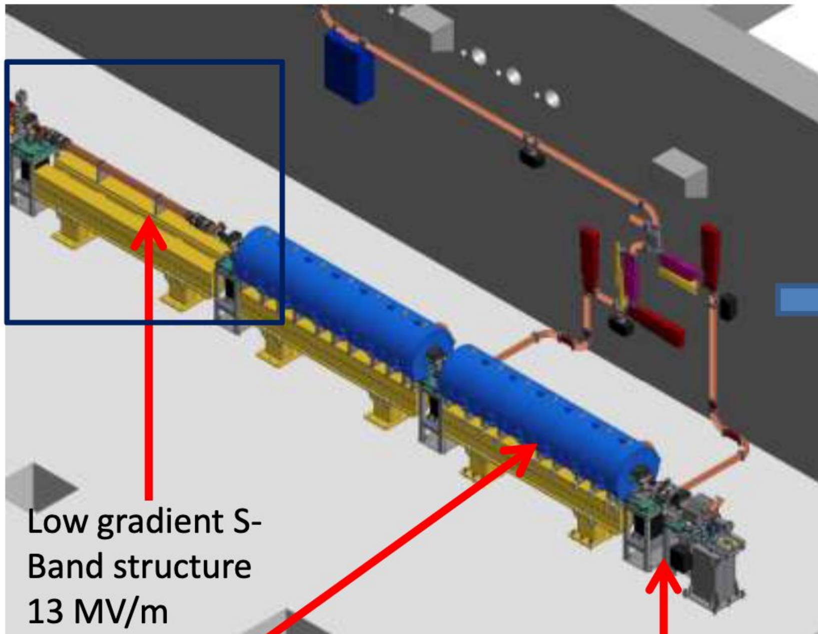


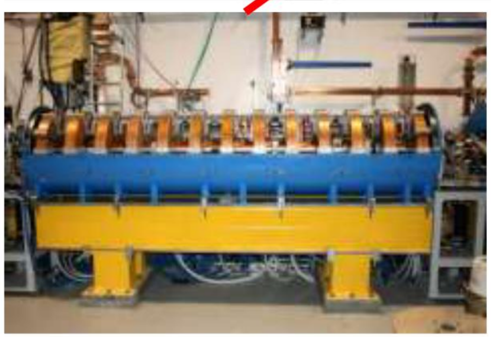




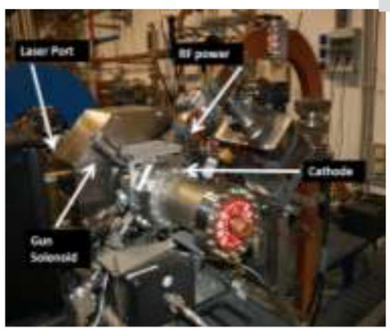
C-BAND ACCELERATING SYSTEM @ SPARC

The **energy upgrade of the SPARC** photo-injector at LNF-INFN from 150 to more than 240 MeV will be done by replacing a low gradient S-Band accelerating structure with two C-band structures. The structures are **TW and CI**, have symmetric axial input couplers and have been optimized to work with a SLED RF input pulse. In the SPARC photoinjector the choice of the C-band for the energy upgrade was dictated by the opportunity to **achieve a higher accelerating gradient**, enabled by the higher frequency, and to **explore a C-band acceleration combined with an S-band injector** that, at least from beam dynamics simulations was very promising in terms of achievable beam quality.

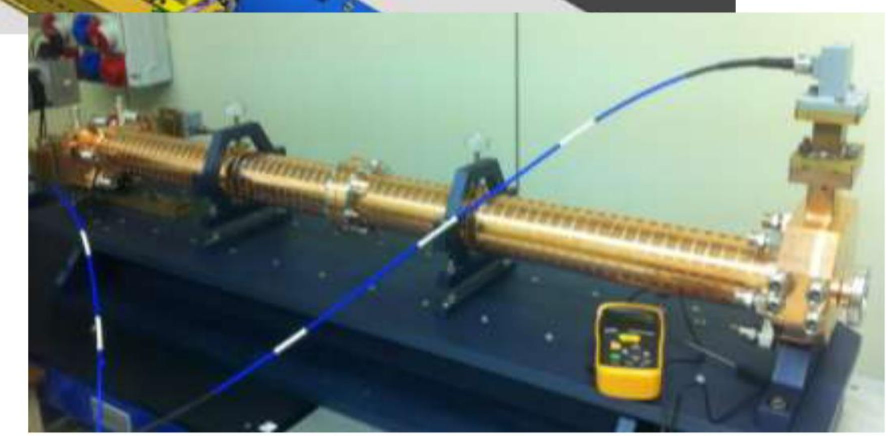




S-Band SLAC-type structure
22 MV/m



S-Band gun 120 MV/m



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Guidelines to the LH design

Compact

Beam energy:

- at as *low energy* as possible since damping ~ $\Delta E_{LH}/E_0$ (< 200 MeV or so)
- better control if *out of* the beam space charge regime (> 80 MeV or so)

Laser:

- short lambda for more efficient smearing of the laser modulation (1 or 0.5 micron)
- must tolerate 1 kHz rep. rate (expected ~10 mW average power)

Chicane:

- bending angle is a compromise between length, laser injection, smearing and CSR-induced emittance growth (typically < 6 deg)
- Should include 2 view screens and 2 BPMs

Undulator:

- undulator period has to match the beam energy (typically, few cm)
- the number of periods is a compromise between max. heating and coupling to the laser bandwidth (~10 periods are usually enough)

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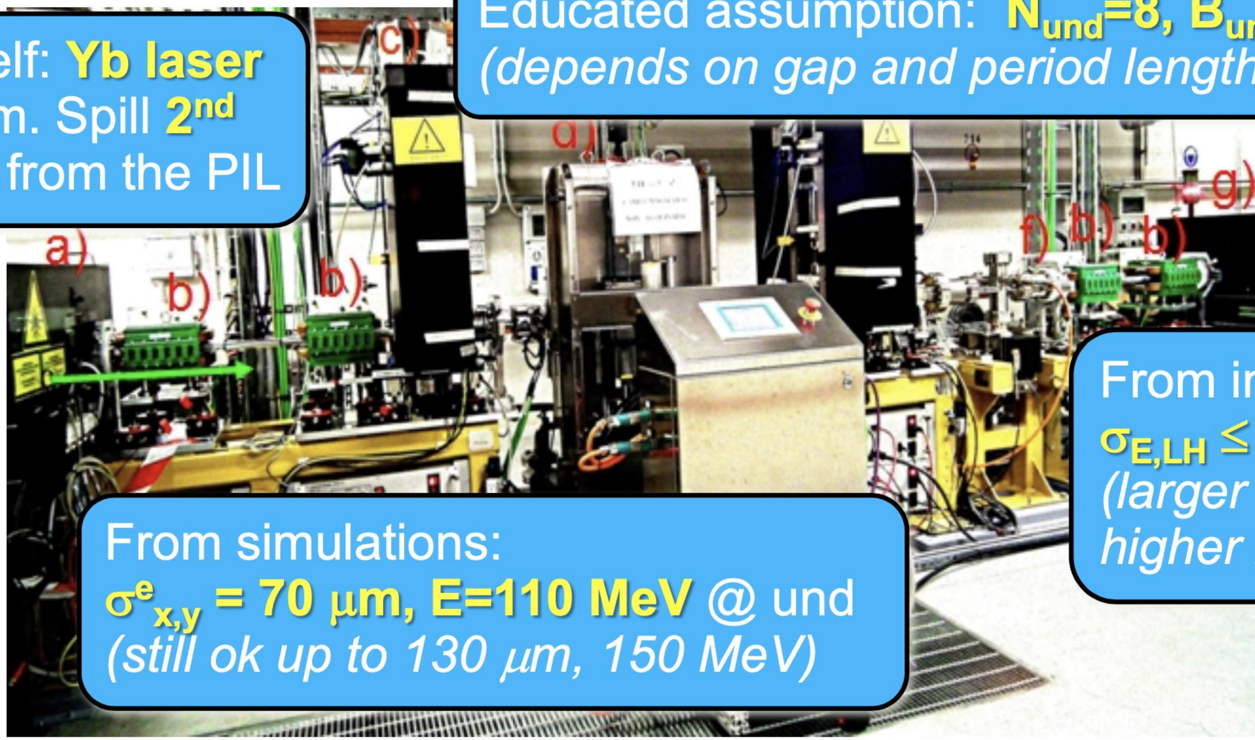
Educated assumptions

Compact

On the shelf: **Yb laser** @ 1064 nm. Spill **2nd harmonic** from the PIL

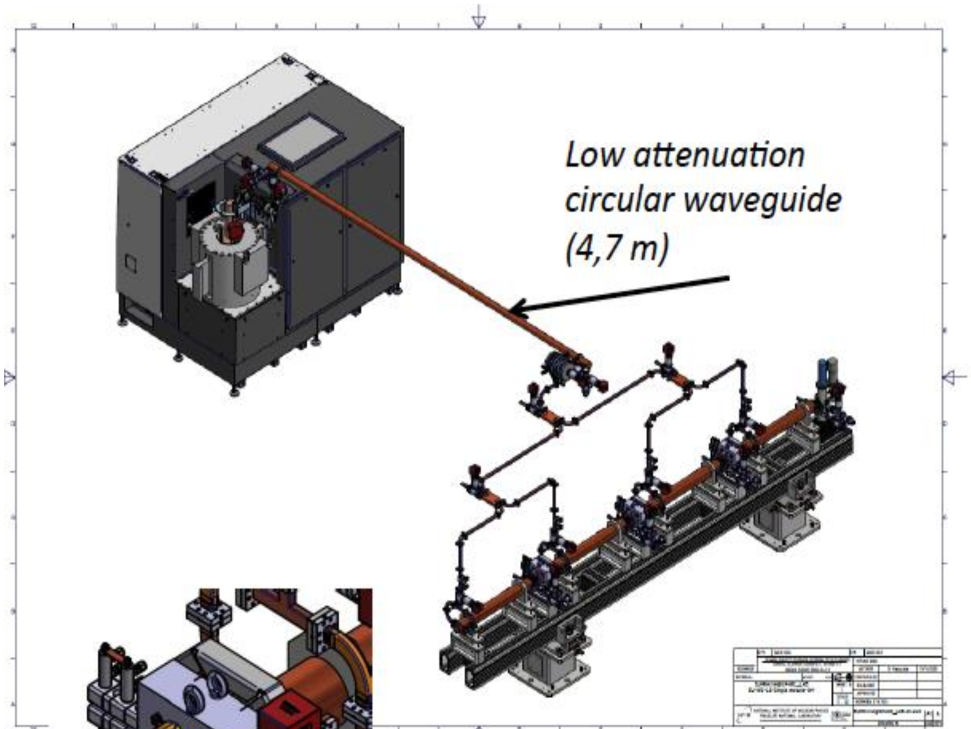
Educated assumption: **N_{und}=8, B_{und} = 0.4 T**
(depends on gap and period length)



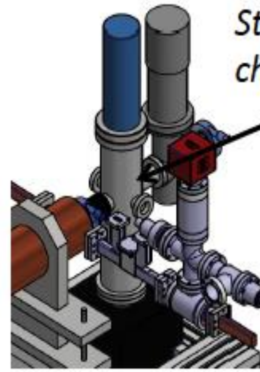
From instability model:
$\sigma_{E,LH} \leq$ 30 keV
(larger values from higher laser energies)

From simulations:
$\sigma^{e}_{x,y}$ = 70 μm, E=110 MeV @ und
(still ok up to 130 μm, 150 MeV)

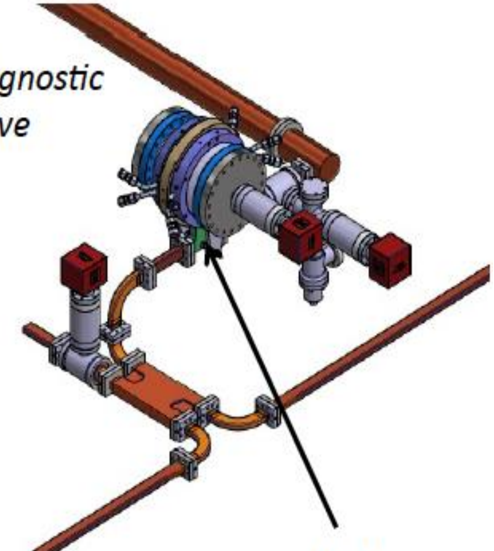
X BAND MODULE LAYOUT



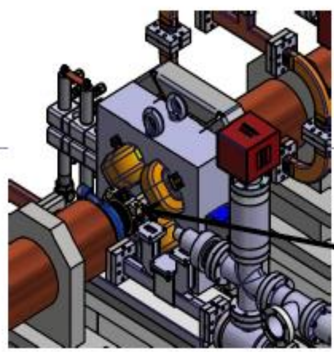
Low attenuation circular waveguide (4,7 m)



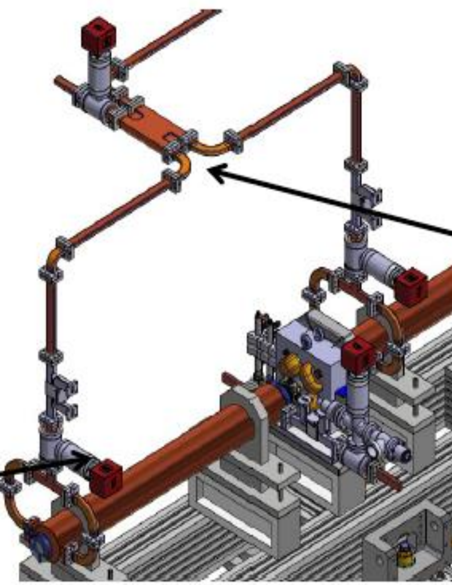
Standard Diagnostic chamber+valve



BOC



Striplines integrated into the QUAD (WP 14)



hybrid

pumps

NB: two version of the module: Low and High Energy (QUAD length)

E. Di Pasquale, G. Di Raddo

Courtesy D. Alesini

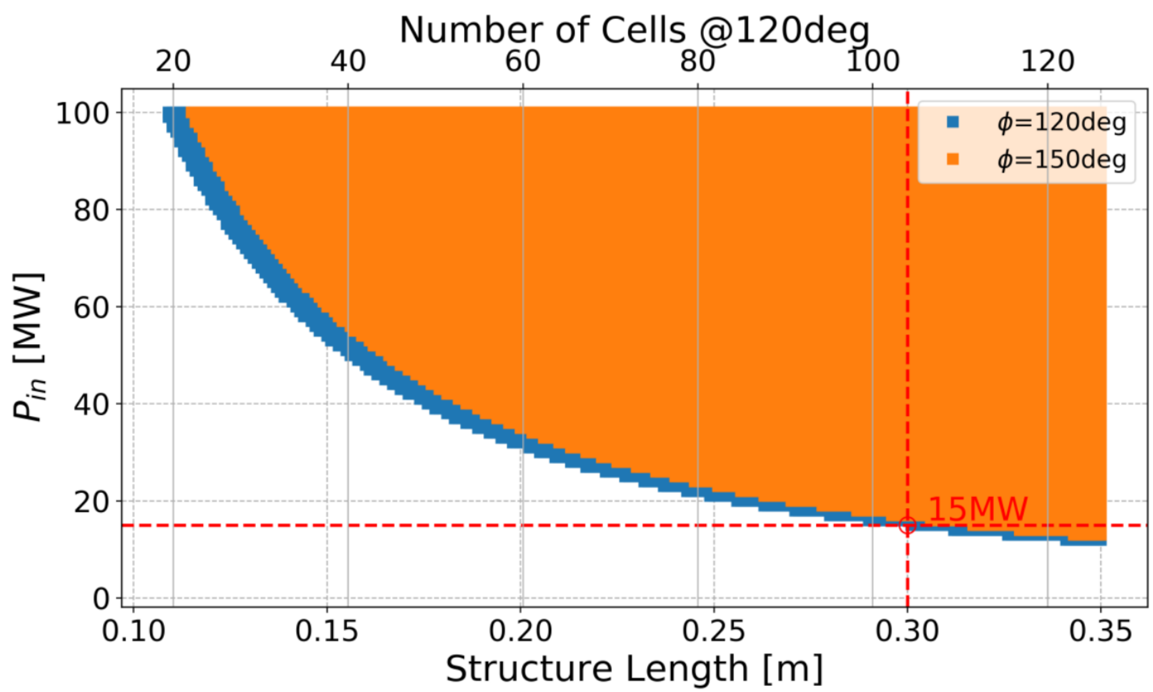
Travelling wave structures

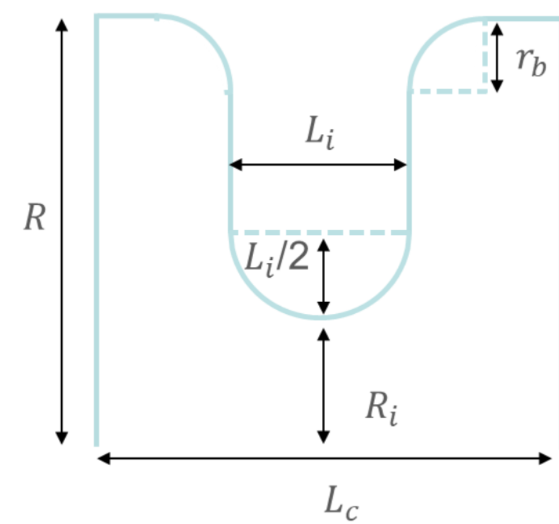
A 2pi/3 30 cm structure provides the required voltage (12.75 MV) with the 15 MW of RF power supplied by the RF source/ pulse compressor

- 1x 30cm with 15MW for 12.5 MV (41.7 MV/m)
- Ep 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 $E_z = 1\ MV/m$





Bunch Compressor 1

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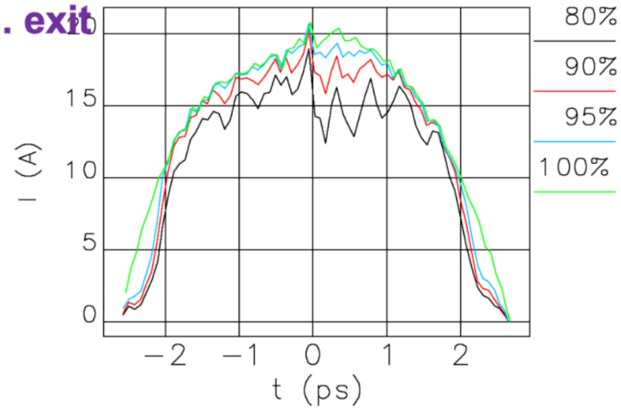
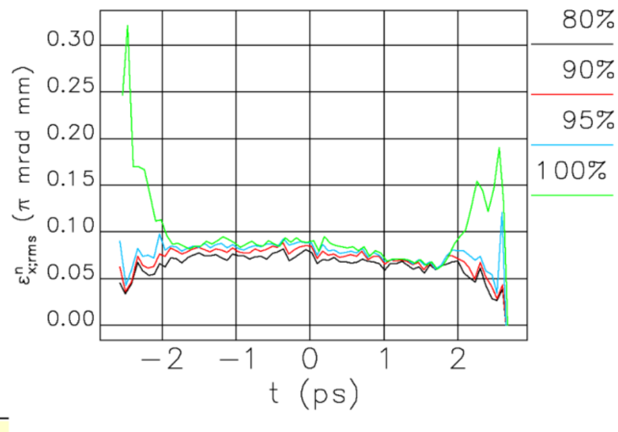
With CSR on:

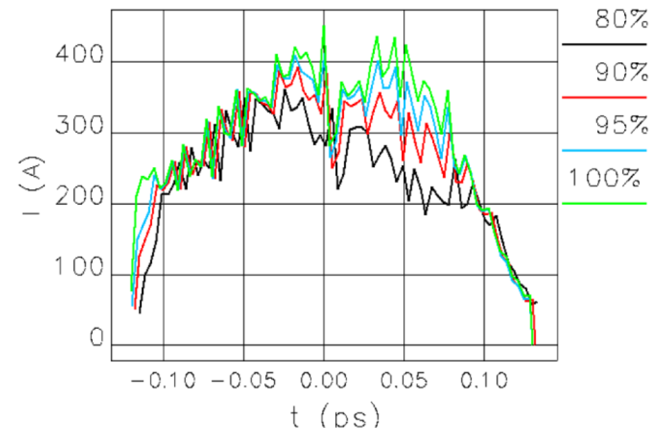
Compact

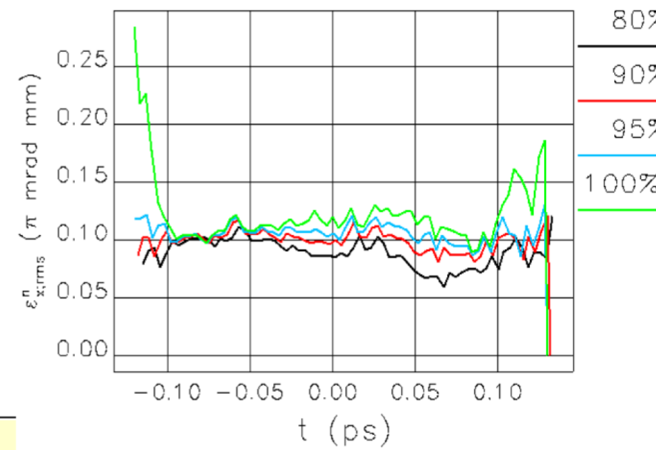
Low energy Ph-Inj. exit





BC1 exit: R_{56}= -20.6 mm, T_{566} = 31 mm





Appendix

- **Task 3.1 - Gun Design (RF, Solenoid, Cathode, Laser, Diagnostics)** => ~~D3.1 M18~~ => D3.4 M39
  a) S-Band Gun RF Design (**CNRS** + IASA+UAIAT-INFN+ALBA)
  b) C-Band Gun RF Design (INFN +IASA+Sapienza)
  c) X-Band Gun RF Design (**CSIC-IFIC** + UAIAT+ Sapienza)
  d) DC Gun Design (**TU/e**)
  e) Laser/Photocathode (IASA+CNRS+INFN)

- **Task 3.2 - Compressor Design (Velocity Bunching, Magnetic Chicane))** => ~~D3.2 M18~~ => D3.4 M39
  a) S-Band Velocity Bunching (**TU/e** + IASA+ALBA)
  b) C-Band Velocity Bunching (INFN +IASA+TU/e)
  c) X-Band Velocity Bunching (**Sapienza**+CERN+IASA+INFN)
  d) Magnetic Compressor & Laser Heater (ST + CERN+INFN+CNRS)

- **Task 3.4 - : RF Linearizer Design** => ~~D3.2 M18~~ => D3.4 M39
  a) X-Band RF Linearizer Design (**Sapienza**)
  b) K-Band RF Linearizer Design (ULANC +Sapienza)
  c) Passive linearizer (**CNRS)**

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Compact

Thank you!

CompactLight@elettra.eu www.CompactLight.eu

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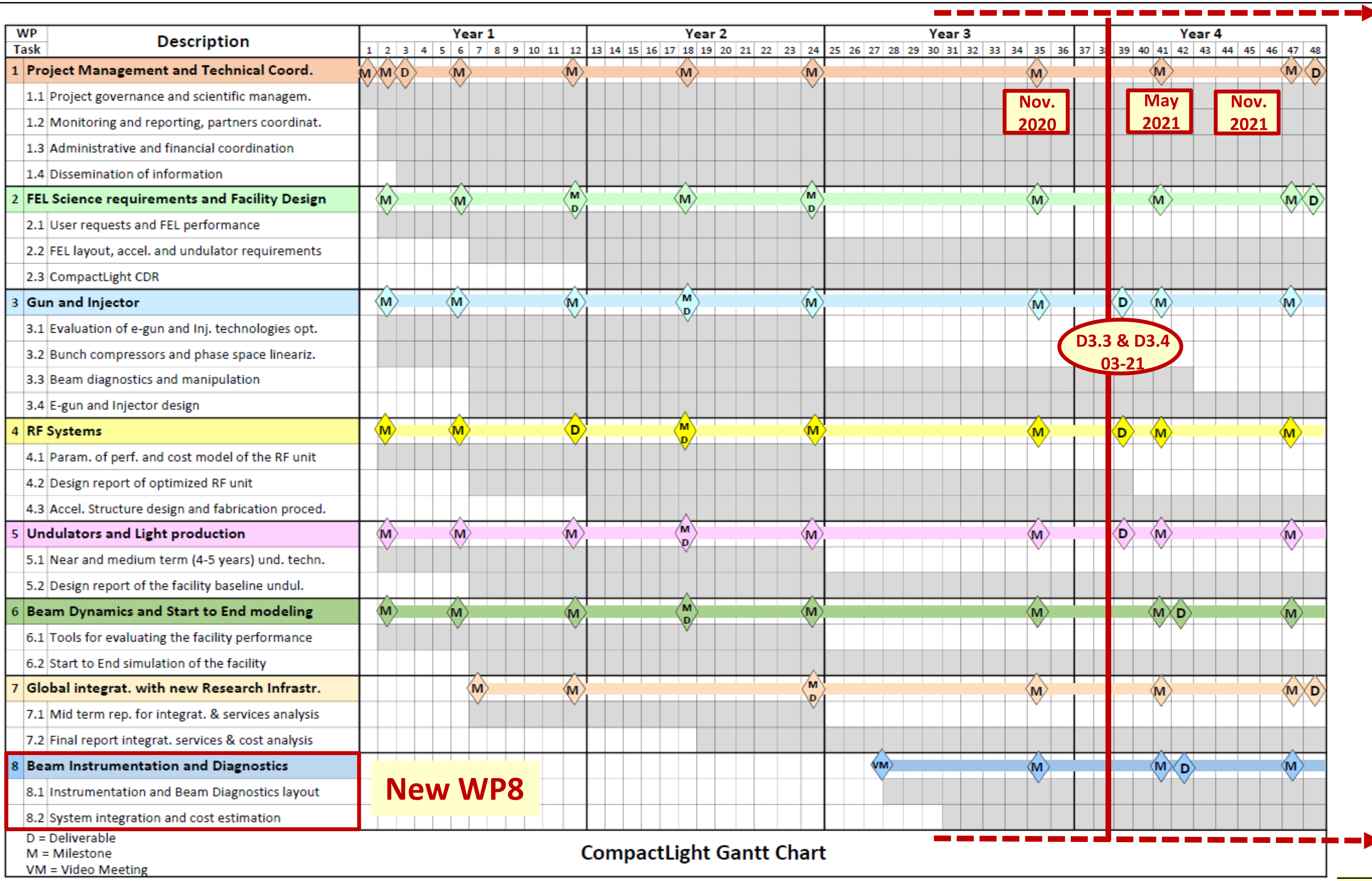
New XLS Gantt Chart



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To Do

Compact

- Laser/Cathode system survival at 1 kHz
- Include fringing fields in the gun region
- C-band Power source OK
- Verify LH not excluding possible VB
- X-band module @ 30 MV/m after LH =>7.5 m less
- Fix the configuration of the k-band linearizer @1 kHz
- **2 bunches Wakes**
- BC1