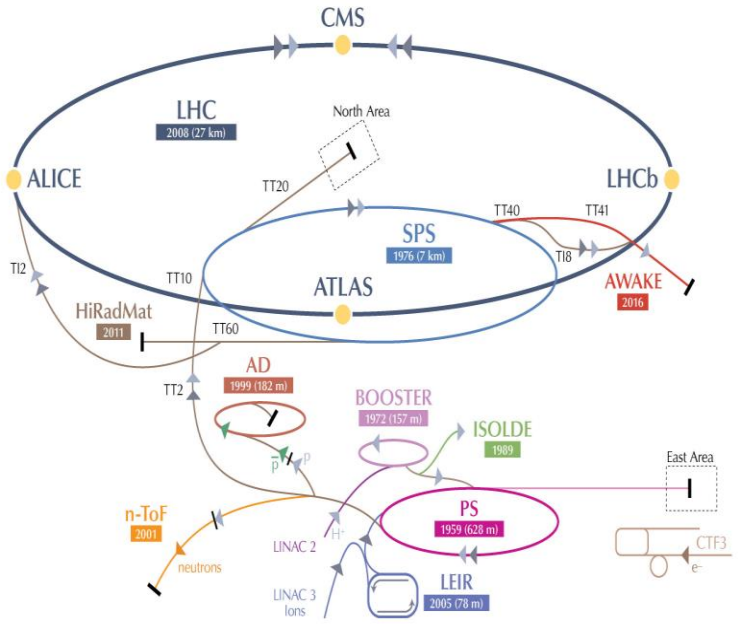
AWAKE Electron injectors for Run 2

CLIC Project Meeting, 5th October 2021

Steffen Doebert, SY-RF

AWAKE at CERN



Advanced WAKEfield Experiment

- Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
- Collaboration of 23 institutes world-wide
- Approved in August 2013

AWAKE Run 1 (2016-2018):

✓ 1st milestone: Demonstrate seeded self-modulation of the proton bunch in plasma (2016/17)

✓ 2nd milestone: Demonstrate electron acceleration in plasma wakefield driven by a self-modulated proton bunch. (2018)

AWAKE Run 2 (2021 – ~2028):

Accelerate an electron beam to high energies (gradient of 0.5-1GV/m) while preserving the electron beam quality and demonstrate scalable plasma source technology.

After 2028: First application of the AWAKE-like technology:

Once AWAKE Run 2 demonstrated: fixed target experiments for e.g. dark photon search.

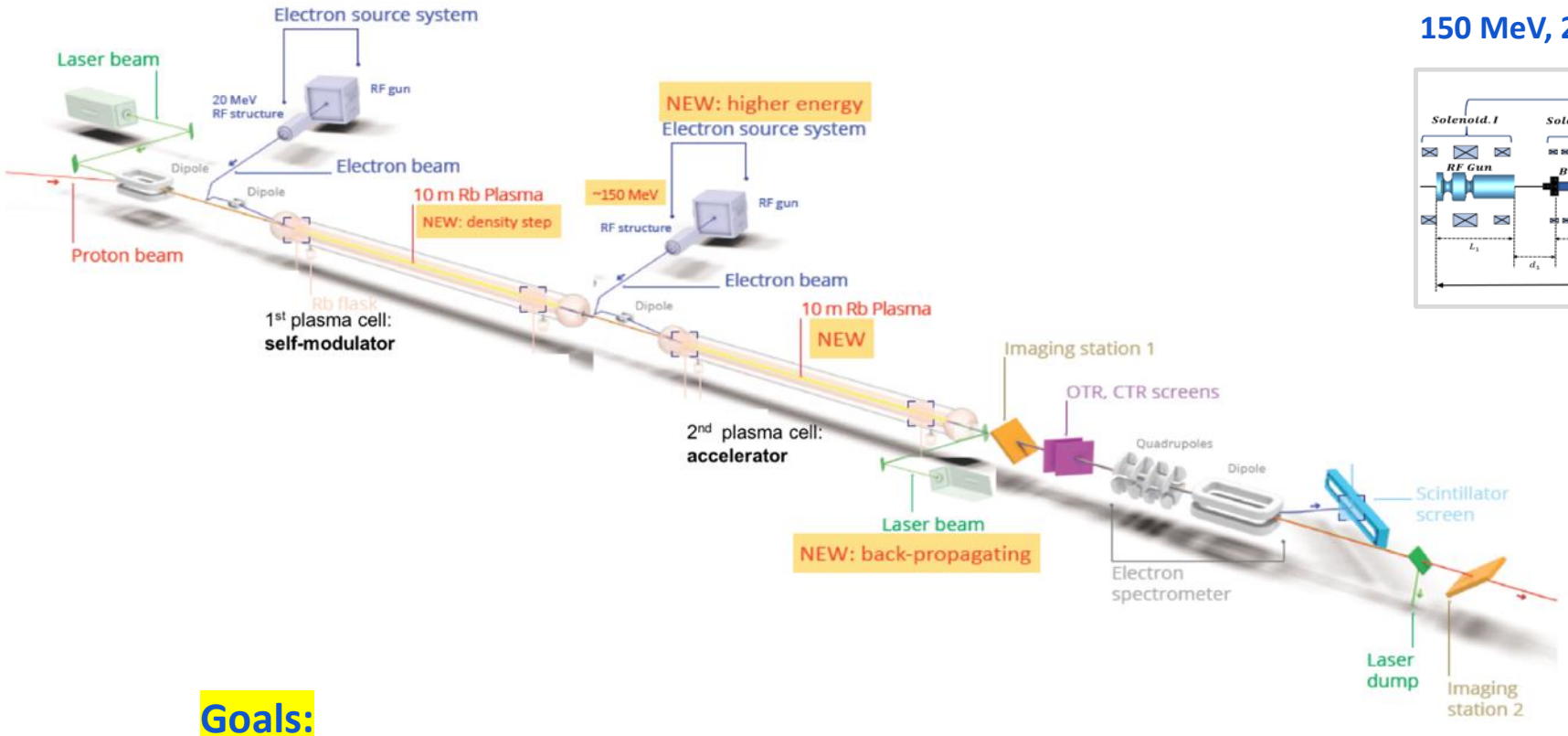
AWAKE Run 2

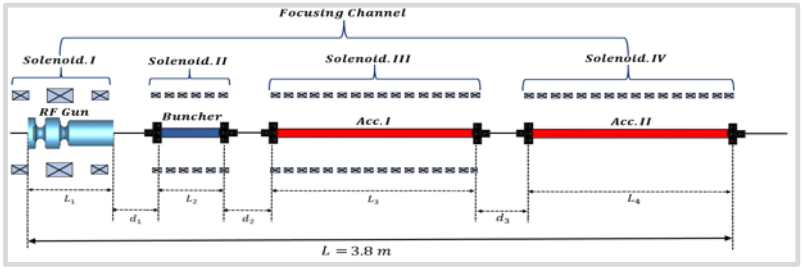
➔ **Demonstrate possibility to use AWAKE scheme for high energy physics applications in mid-term future!**

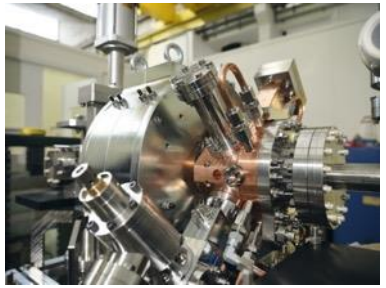
➔ Start 2021! Staged program for ~ 10 years

➔ **Need to work in blow-out regime and do beam-loading**

➔ **New electron beam based on x-band:**
150 MeV, 200 fs, 100 pC, σ = 5.75 µm







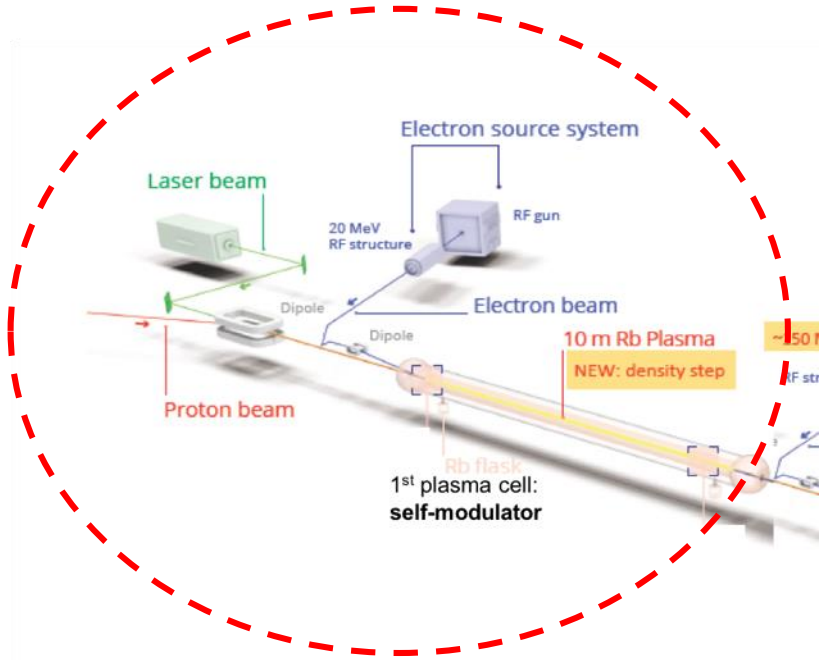
Goals:

Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)

Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)

Demonstrate scalable plasma source technology (e.g. helicon prototype)

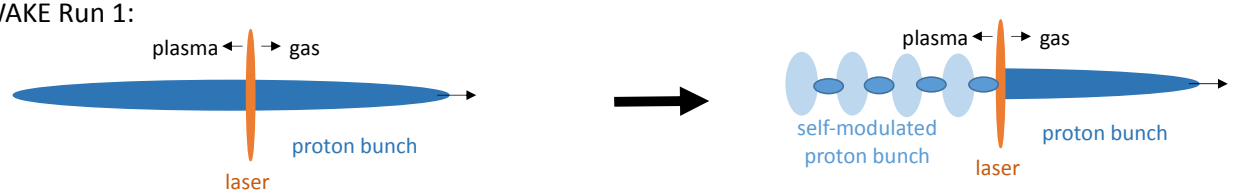
AWAKE Run 2a: Demonstrate Electron Seeding of Self-Modulation in First Plasma Cell



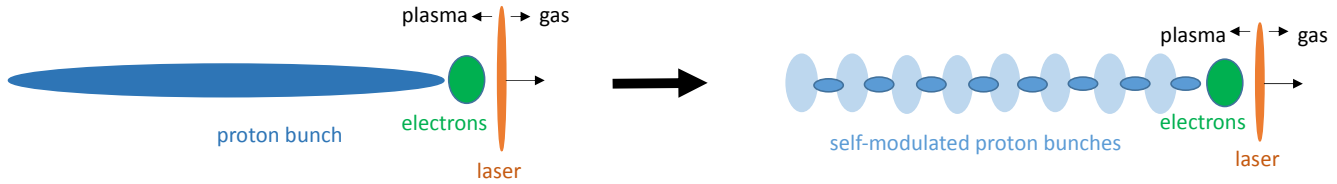
Why electron bunch seeding:

→ Modulates entire proton bunch with phase reproducibility

AWAKE Run 1:



AWAKE Run 2:



→ Run 2a: use the existing AWAKE Facility

→ **Physics program in ~2021/2022**

AWAKE Run 2

- Run 2a: Demonstrate Electron Seeding of Self-Modulation in First Plasma Cell
  2021/2022 using existing facility

- Run 2b: Demonstrate Stabilization of Micro-Bunches with a Density Step
  2023/2024 using existing facility, new plasma cell

- Run 2c: Demonstrate Electron Acceleration and Emittance Preservation
  New injector in extended exp. area 2025/2026, physics starts 2027/2028

- Run 2d: Demonstrate Scalable Plasma Sources; towards physics applications
  > 2029

The latest parameters for both injectors

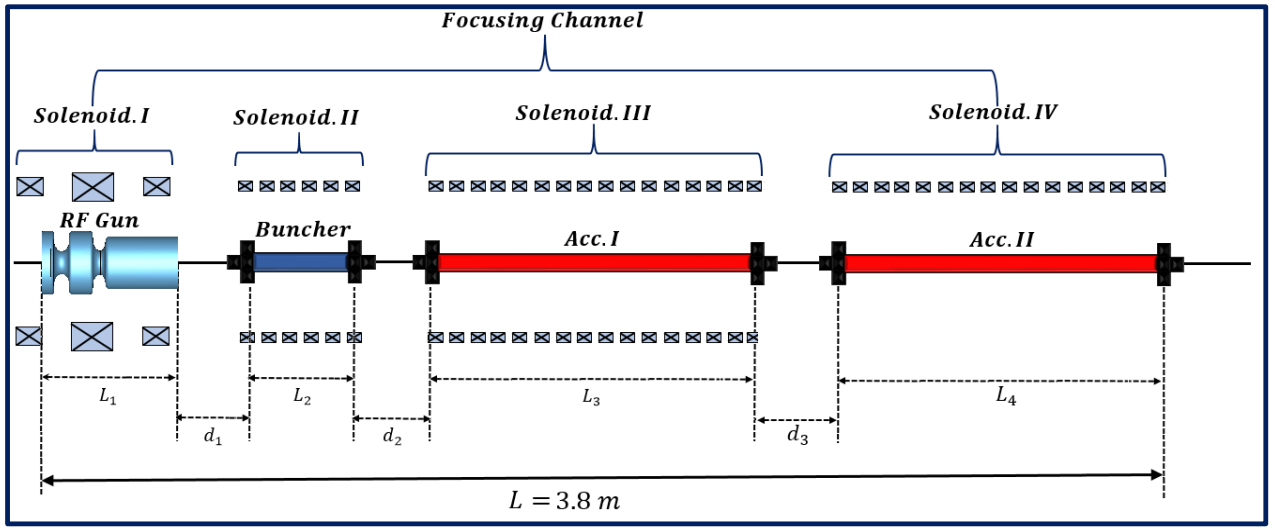
Working documents held by Rebecca (Injector 2, EDMS ?) and John (Injector 1, EDMS 2417022)

	Beam Energy	Energy Spread	Energy stability	RMS Bunch Length	Bunch Charge	Emittance	Beam size plasma focus
Injector 1	18.5 MeV	0.5 %	1 x 10^{-2}	$\approx 2-3\ ps$	100 – 600 pC	2 - 5 μm	~ 190 μm
Injector 2	150 MeV	0.2 %	1 x 10^{-3} ?	$\approx$ 200 – 300 fs	100 pC	2 μm	5.75 μm

- Energy as high as affordable ?
- Energy spread as low as possible
- Energy stability as good as possible
- Emittance reasonably low, no need for ultra-low

Reference design

- Well advanced concept and beam dynamics design



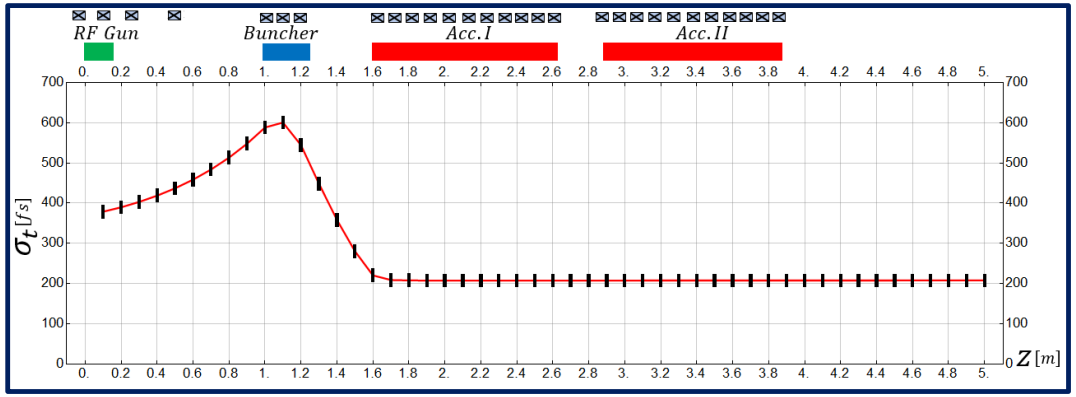
Laser parameters

$\lambda[nm]$	$w[ev]$	$r[mm]$	$t[ps]$	q[nc]
262	4.31	1.0	$1.0 - 5.0$	0.1-1.0

RF parameters

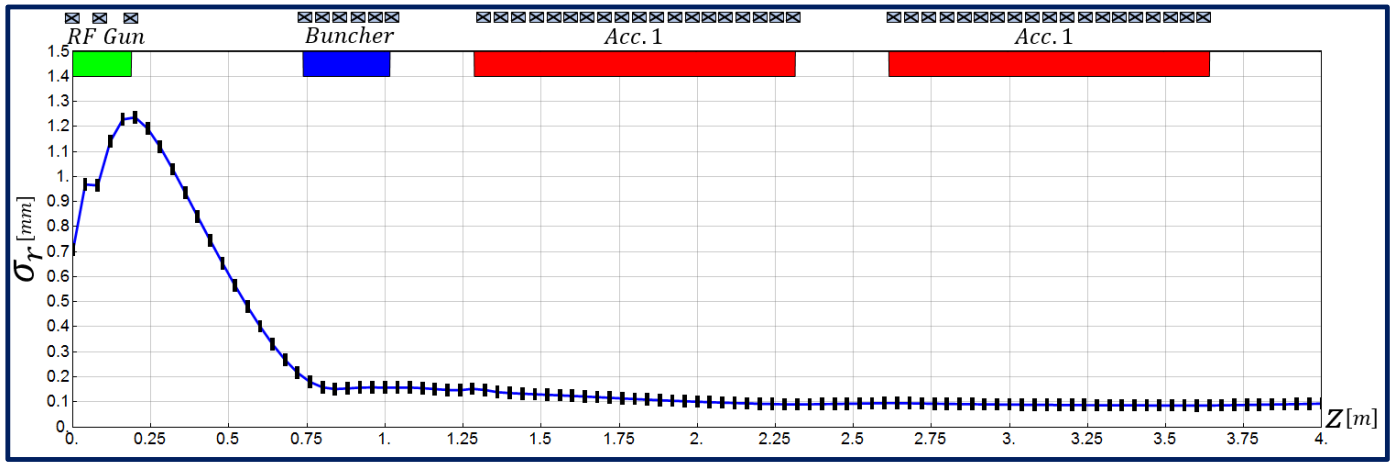
Parameter	RF Gun	Buncher	Acc. I	Acc. II
Frequency	3.0	12.0	12.0	12.0
Gradient	$120MV/m$	$\underline{35MV/m}$	$80MV/m$	$80MV/m$
N. Cell	1.5	30	120	120

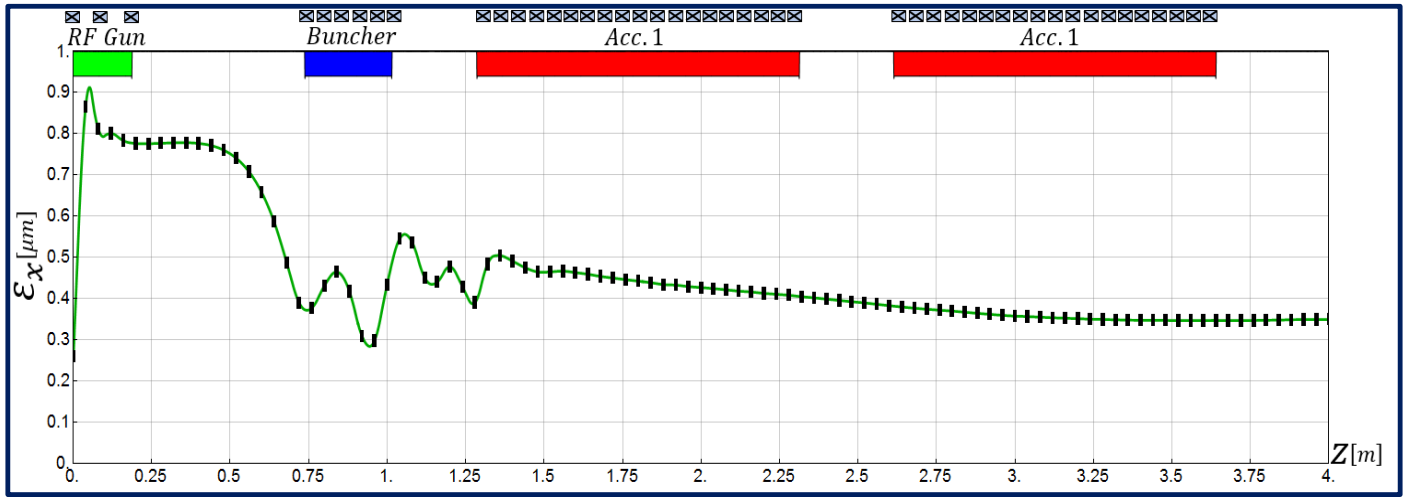
$E_k[MeV]$	$\sigma_r[mm]$	$\sigma_t[fs]$	$\varepsilon_x[\mu m]$	σ_E[%]	$I_{av}[A]$
165	0.14	**207**	0.44	**$\underline{0.09}$**	168

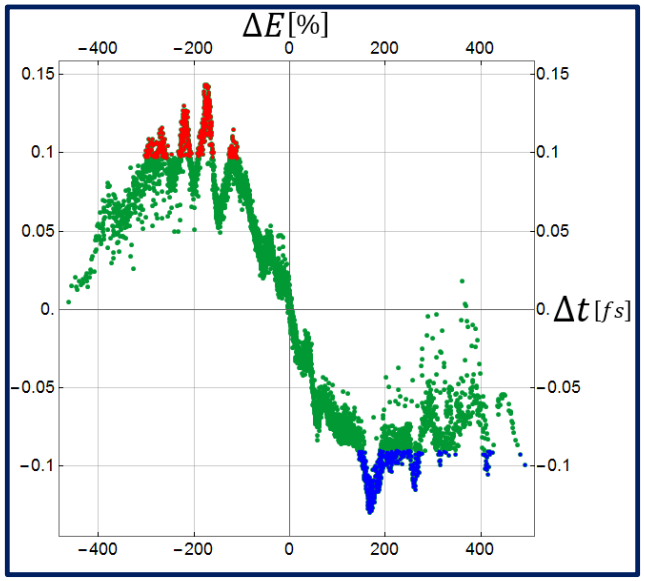


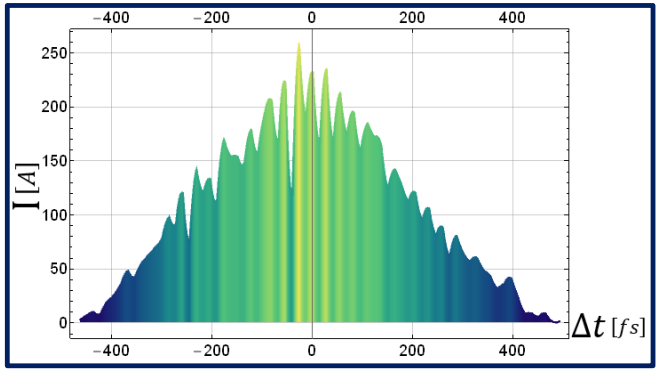
Mohsen Dayyani Kelisani

Reference design



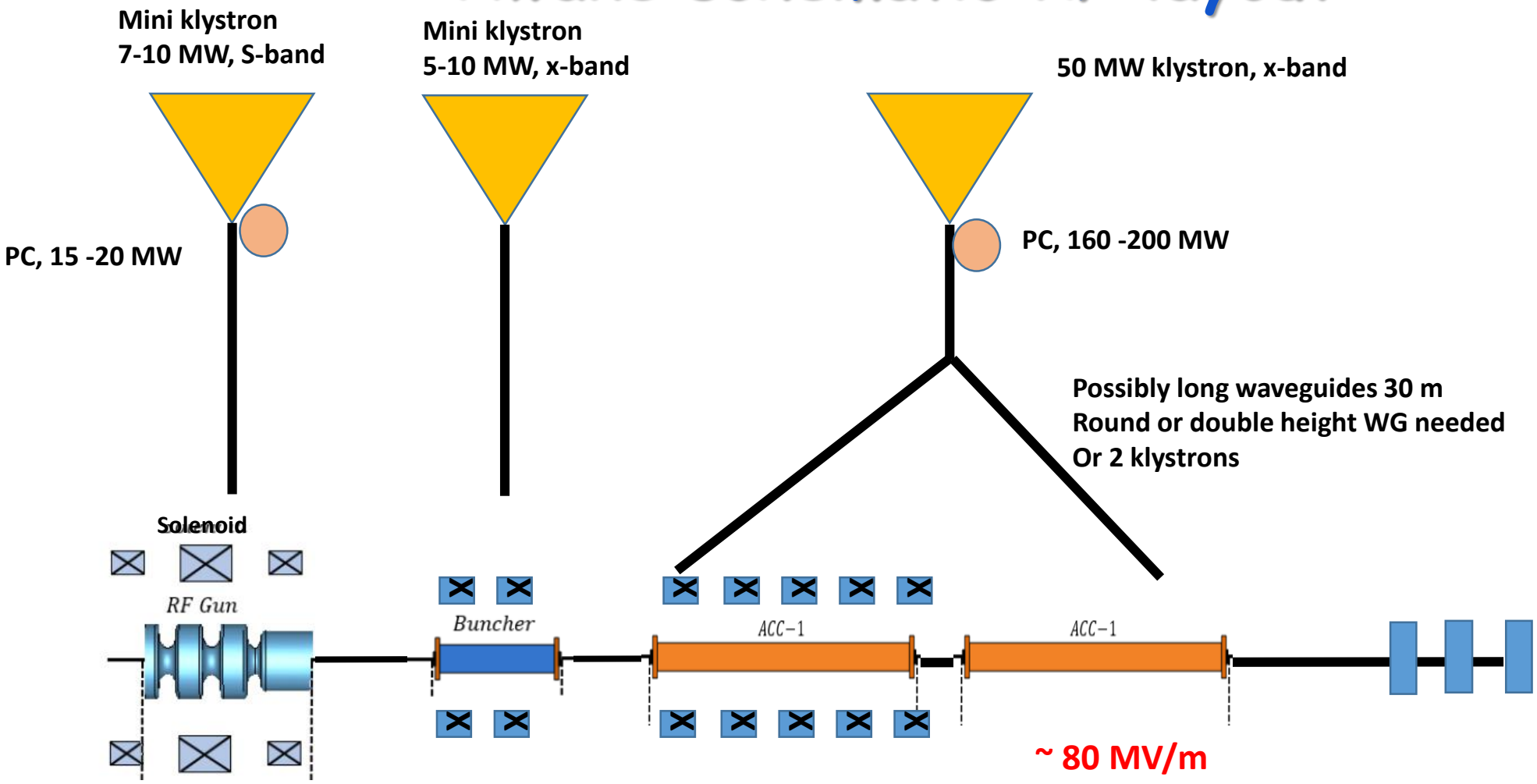






Mohsen Dayyani Kelisani

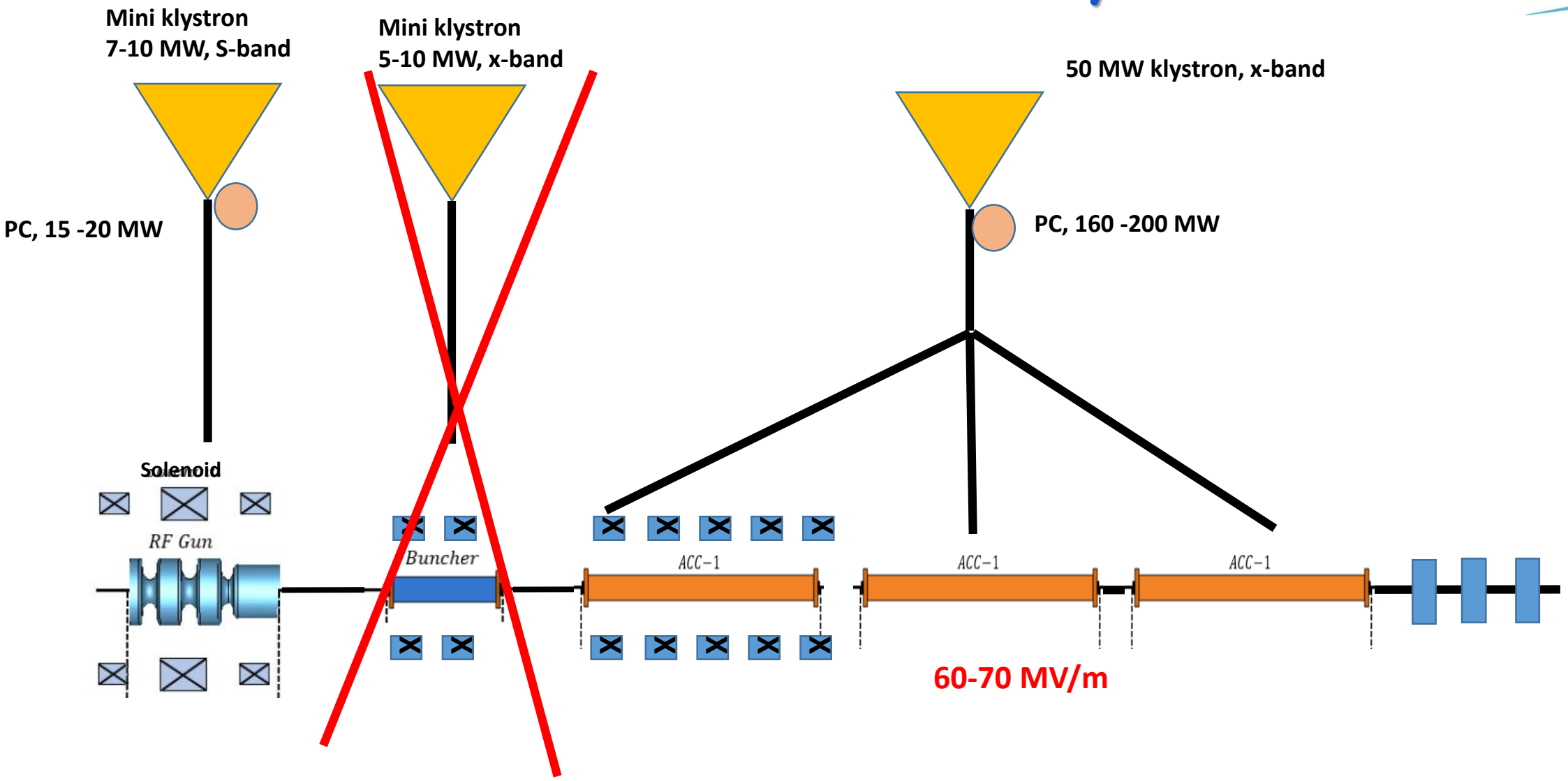
Awake schematic RF layout



Total Energy 150- 160 MeV, 10 Hz rep. rate, single bunch

Will try to use CLIC developed x-band components as much as possible

Awake alternative RF layout



Less power, less cost, lower risk, performance + flexibility ?

X-band structures for AWAKE injector

Structure	Length	No cells	Gradient	Power @	Filling time	Mode
T24	0.25	24	100 MV/m	45 MW	70 ns	$2\pi/3$
PSI lineariser 4.5mm aperture	0.75	72	65 MV/m	80 MW		$5\pi/6$
e-SPS	0.575	69	60 MV/m	30.5 MW	100 ns	$2\pi/3$
CompactLight/ EuPraxia 3. 5 mm aperture	0.9	108	65 MV/m	44 MW	144 ns	$2\pi/3$
Tsinghua	0.63	72	75 MV/m	50 MW		$2\pi/3$
Sinap 3.6 mm aperture	0.94		80 MV/m	80 MW	156 ns	$4\pi/5$

Typical klystron: 50 MW max @ 1.5 us; pulse compressor with phase switch only, factor 4.5 for 150 ns: → 200 MW obtainable
CompactLight: 3 structures at 60 MV/m would need 130 MW

FREIA

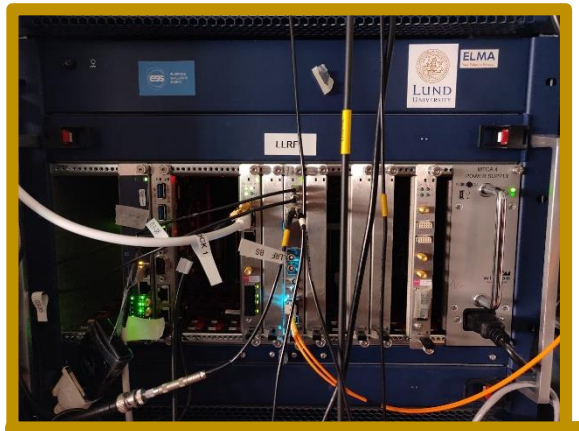
UPPSALA UNIVERSITET

ScandiNova modulator received at FREIA for high voltage and RF measurements on a 7.5 MW klystron. Jitter stability will also be investigated.

Discussions ongoing for the development of a UHV S-band circulator.

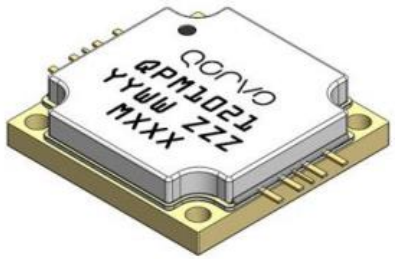
Integrations studies of the 5 modulators and the waveguides ongoing.

Design of the S-band solid state power amplifier ongoing.
It will be followed by the development of the X-band solid state power amplifier.
3 drivers (X-band 1000 W, X-band 300 W and S-band 120 W).



QPM1021

10 – 12 GHz 100 W GaN Power Amplifier



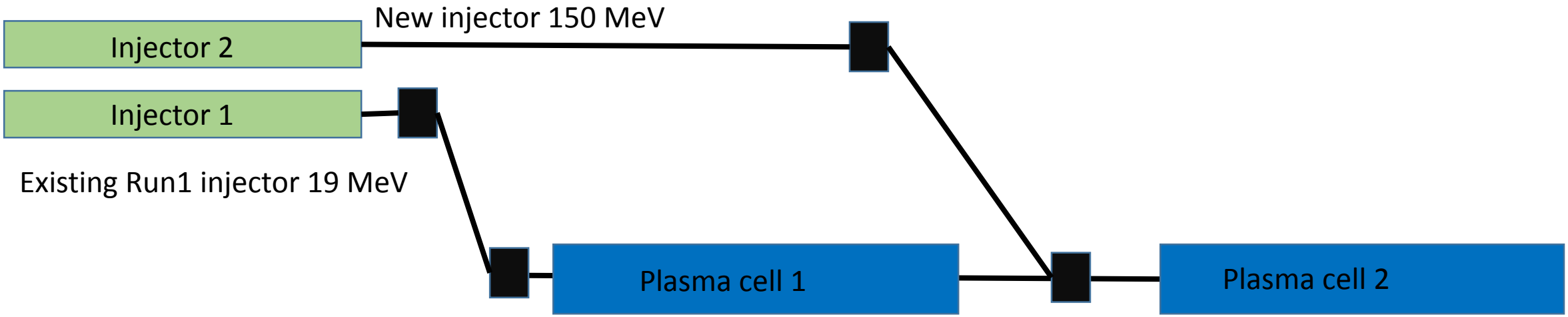
GTVA355001EC

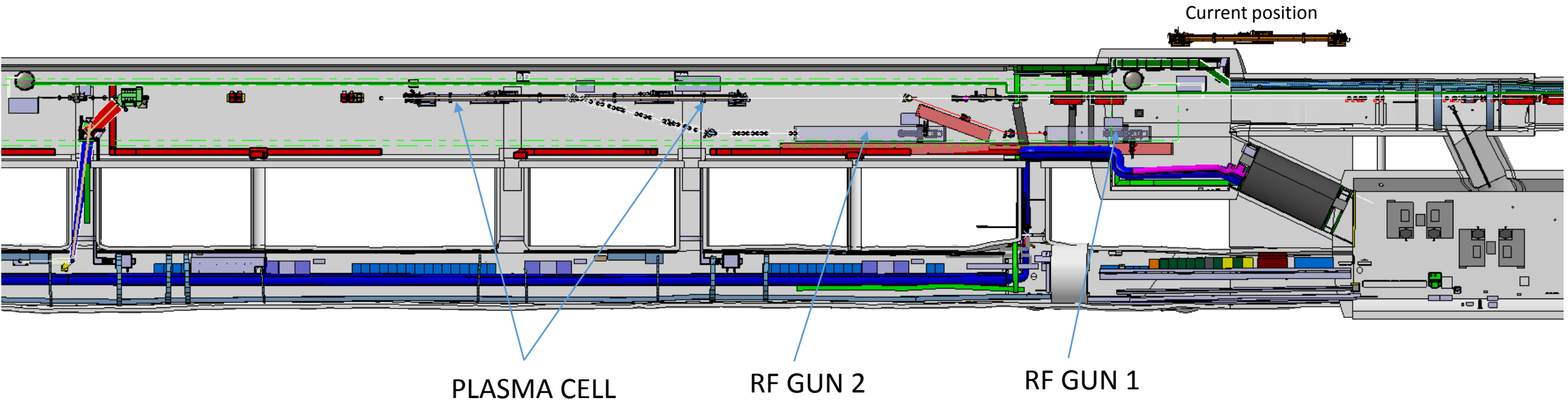
Thermally-Enhanced High Power RF GaN on SiC HEMT
500 W, 50 V, 2900 – 3500 MHz

The work on the low-level RF based on uTCA has started in September 2021.

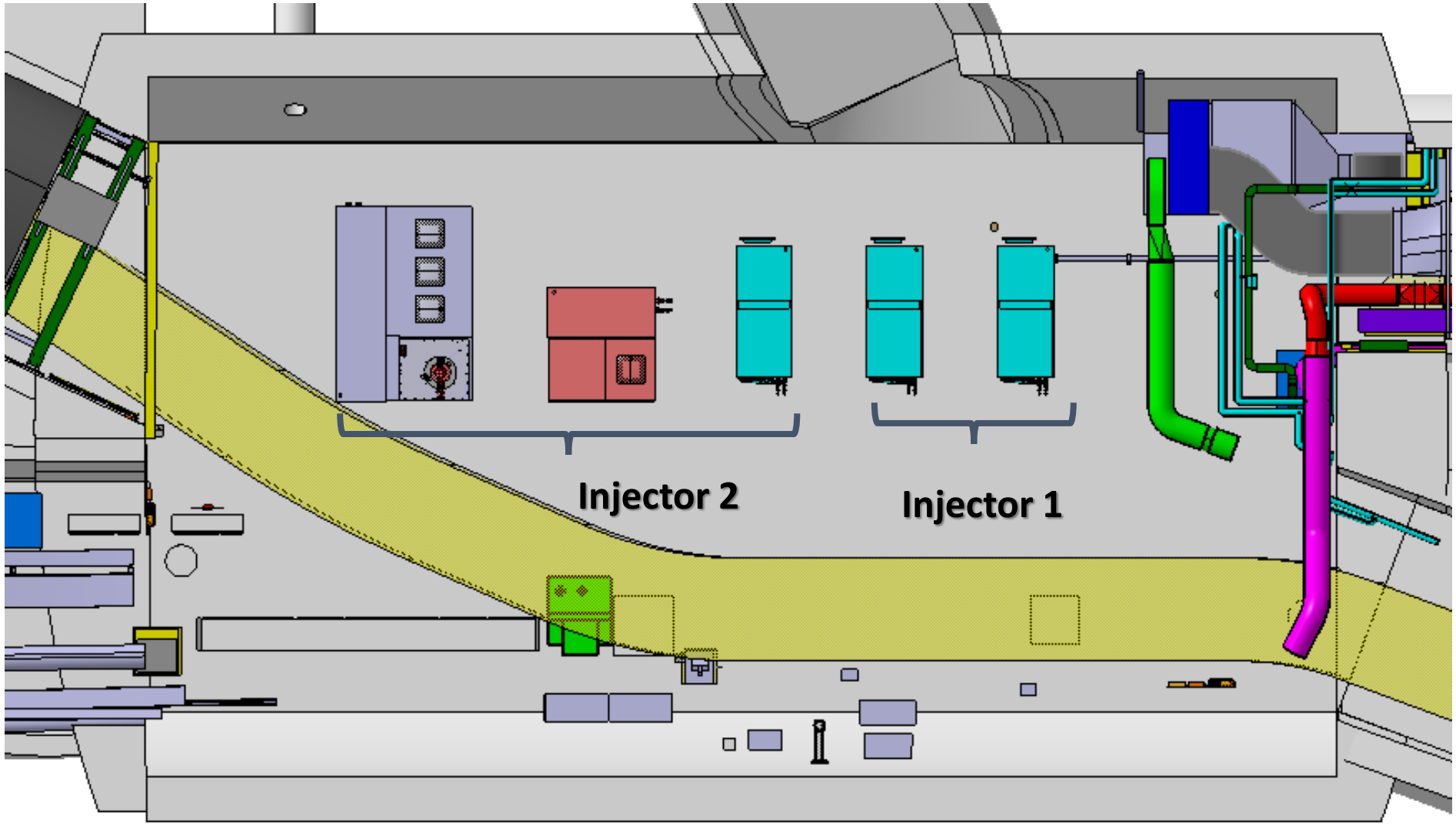
Material bought: uTCA for 2 klystrons/modulators (chassis + cards), needed material for the RF and high voltage measurements on the modulators.

Status of the integration study





New layout proposal from Uppsala



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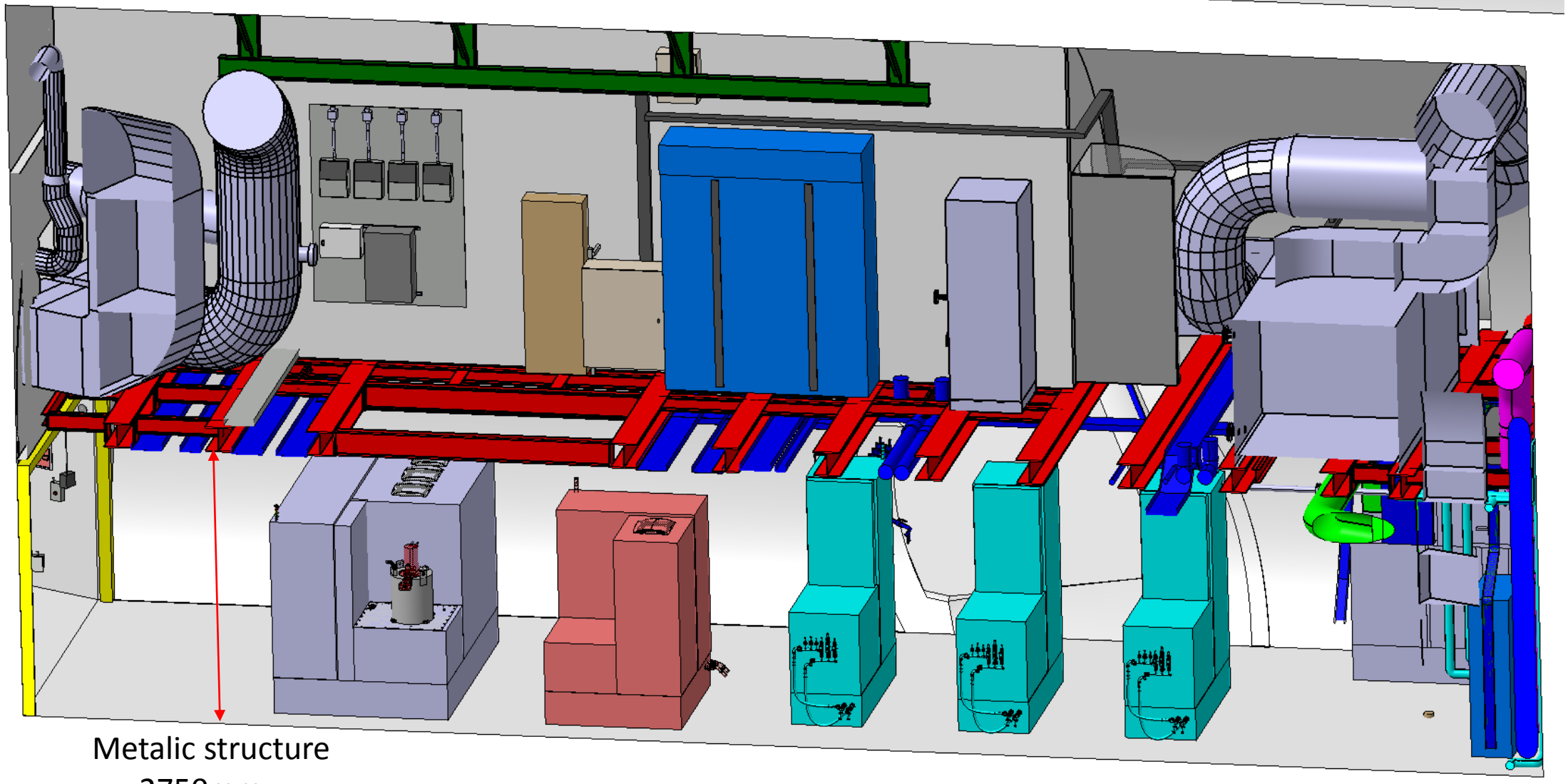
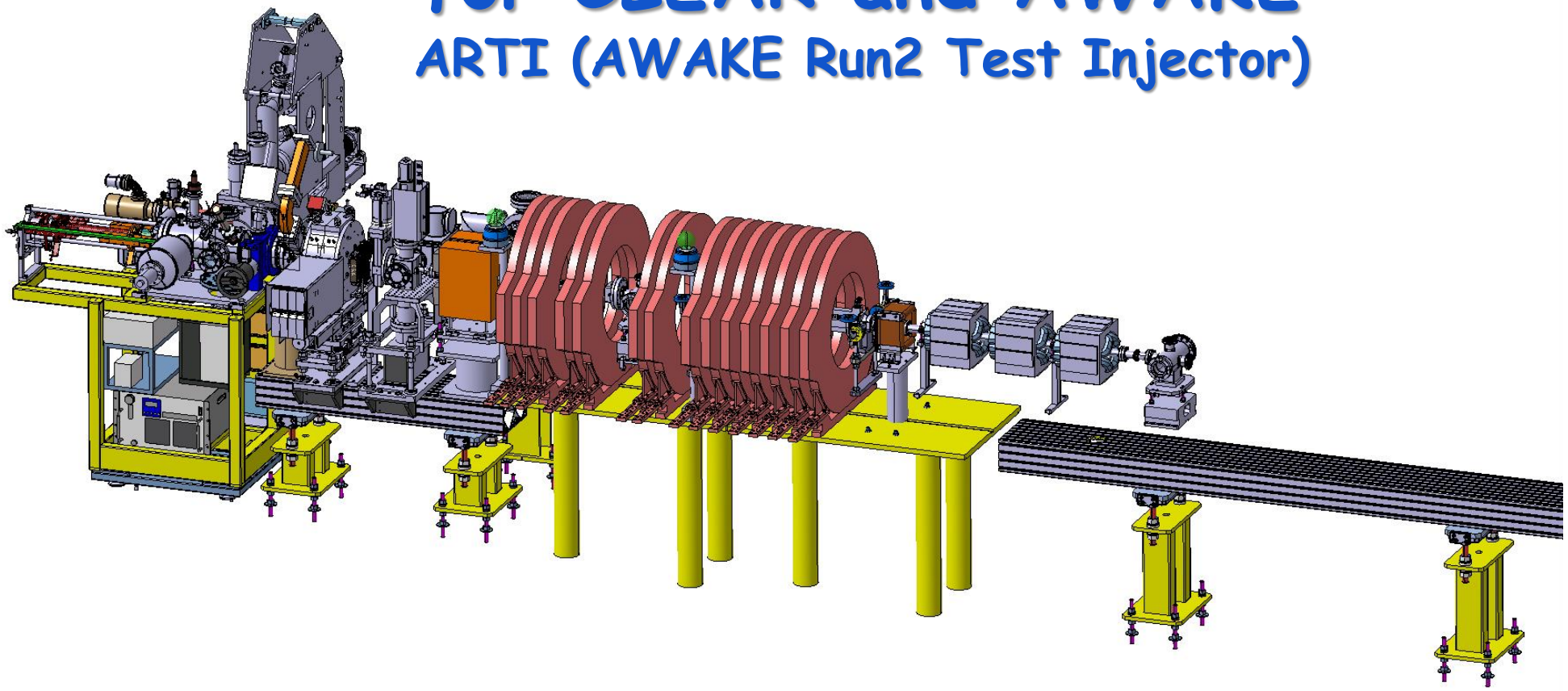


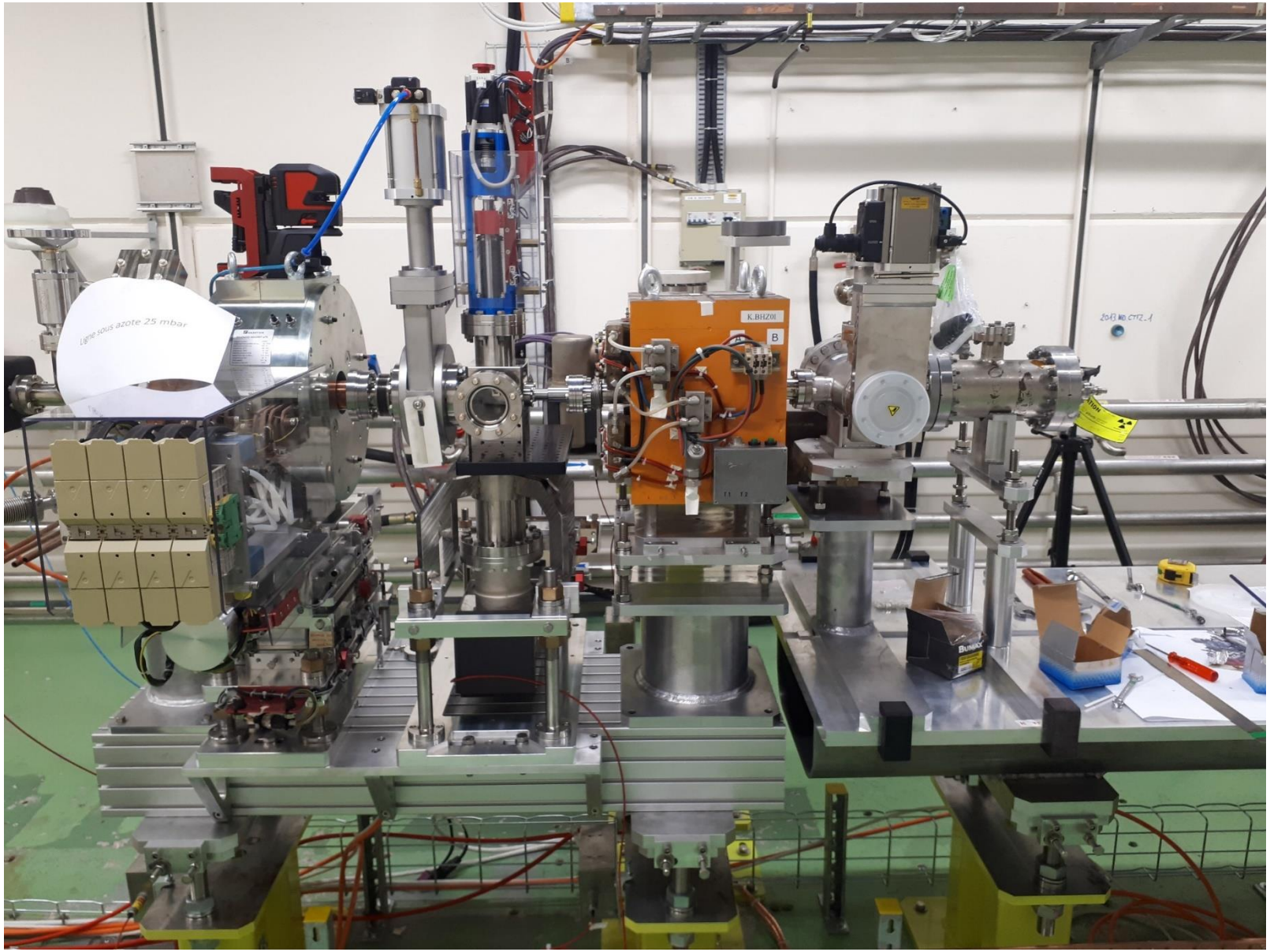
Injector prototype in CTF2 for CLEAR and AWAKE

ARTI (AWAKE Run2 Test Injector)



Reduced scale prototype, 60 MeV, T24 as buncher and PSI-structure for acceleration.
Goal: demonstrate the velocity bunching and emittance preservation with x-band

ARTI in CTF2



Conclusion and Outlook

- Design, Integration and Parameter optimisation for both injectors ongoing solid baseline exists
- First phase of prototype injector installed in CTF2, waiting for high power test Laser being tested and prepared as well, first beam tests after RF conditioning
- The AWAKE collaboration will have to build some x-band high-gradient structures and will use typical x-band high power sources based on “CLIC Technology”
- RUN 2 will give important operational experience of an x-band system. Due to the space constraints, x-band is an enabling technology for the experiment

Some preliminary schedule considerations

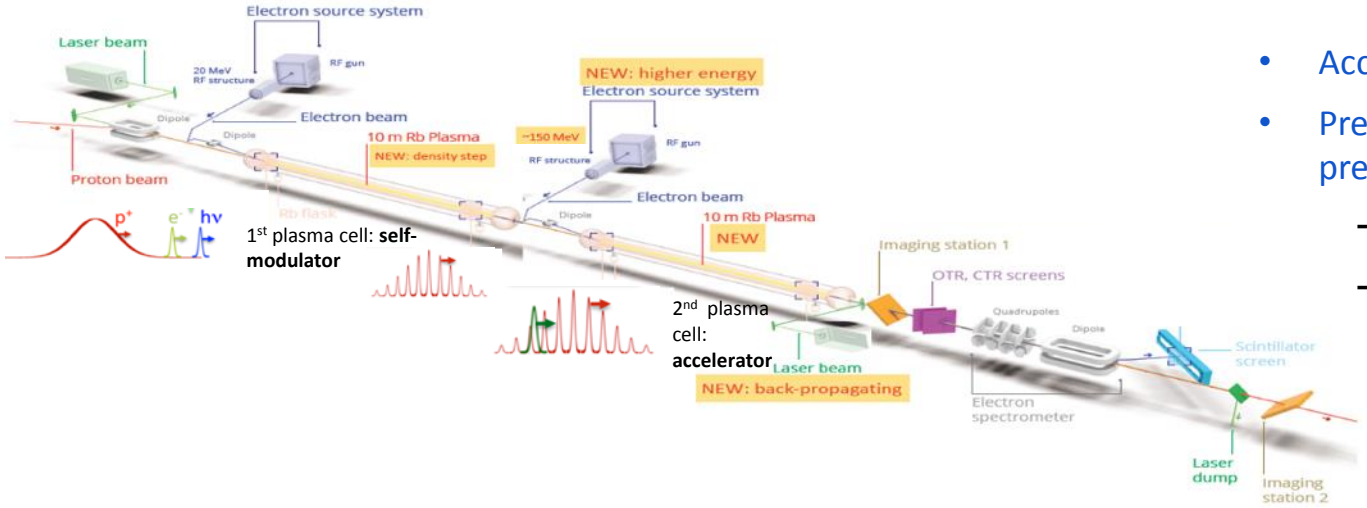
AWAKE 150 MeV								
Schedule	2021	2022	2023	2024	2025	2026	2027	2028
Design								
Mechanical design/Integration								
Procurement								
Installation								
Commissioning								
Start experiments								

CTF2 prototype/CLEAR 60 MeV						
Schedule	2021	2022	2023	2024	2025	2026
Design						
Mechanical design						
Procurement						
Installation						
Commissioning						
Start experiments in CTF2						
Move to CLEAR						
Exp in CEAR						

No more conflicts with CLEAR for time being

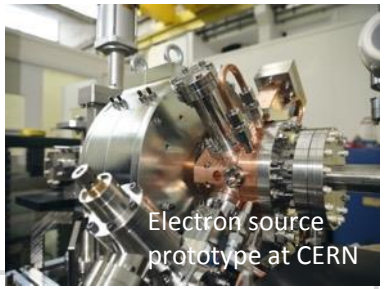
AWAKE Run 2c: Demonstrate Electron Acceleration and Emittance Preservation

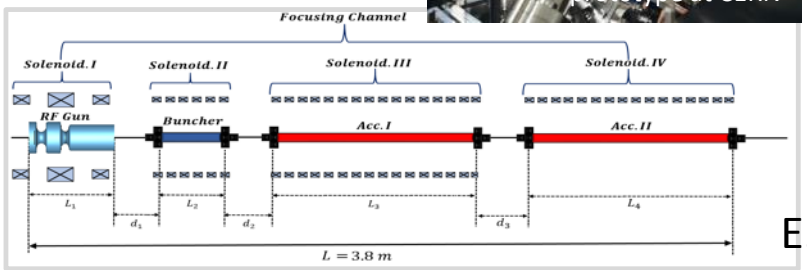
	Beam Energy	Energy Spread	Energy stability	RMS Bunch Length	Bunch Charge	Emittance	Beam size plasma focus
Injector 1	18.5 MeV	0.5 %	1 x 10^{-2}	$\approx 2-3\ ps$	$100\ -600$ pC	2 - 5 μm	$\sim 190\ \mu m$
Injector 2	**150 MeV**	**0.2 %**	**1 x 10^{-3} ?**	**$\approx 200-300$ fs**	**100 pC**	**2 µm**	**5.75 µm**



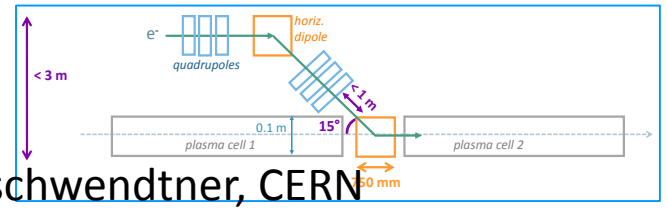
- Accelerate an electron beam to high energy (gradient of 0.5-1GV/m)
- Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)
  - → Need to work in blow-out regime and do beam-loading
  - → New electron beam:150 MeV, 200 fs, 100 pC, σ = 5.75 µm

New electron source:
→ based on X-band
→ Prototyping together with CLEAR





New electron line:
→ Requirement of β = 5 mm at injection.
→ Require achromatic module, with no bunch lengthening.
→ Limit of ~ 3m width set by tunnel width
→ Dipole bending angle > 15°
→ Dipole-quadrupole spacing > 1 m
→ Matching conditions at merging: $\sigma = \sqrt{4.87\ \text{mm} \times \epsilon}$



New laser system:
IR laser beams to ionize the 2nd rubidium vapour source will be injected from downstream counter-propagating to the p-beam.
UV laser beams for producing two electron beams

New beam instrumentation:
Co-propagating e- and p+ beams: position, size measurement (e- beam).
200 fs electron bunches: bunch length measurement.
Witness e- beam injected in 2nd plasma cell: measurement of small (6 µm σ) beam in Rb vapour.

New 2nd plasma cell:
Complex injection region: matching of electron beam to plasma

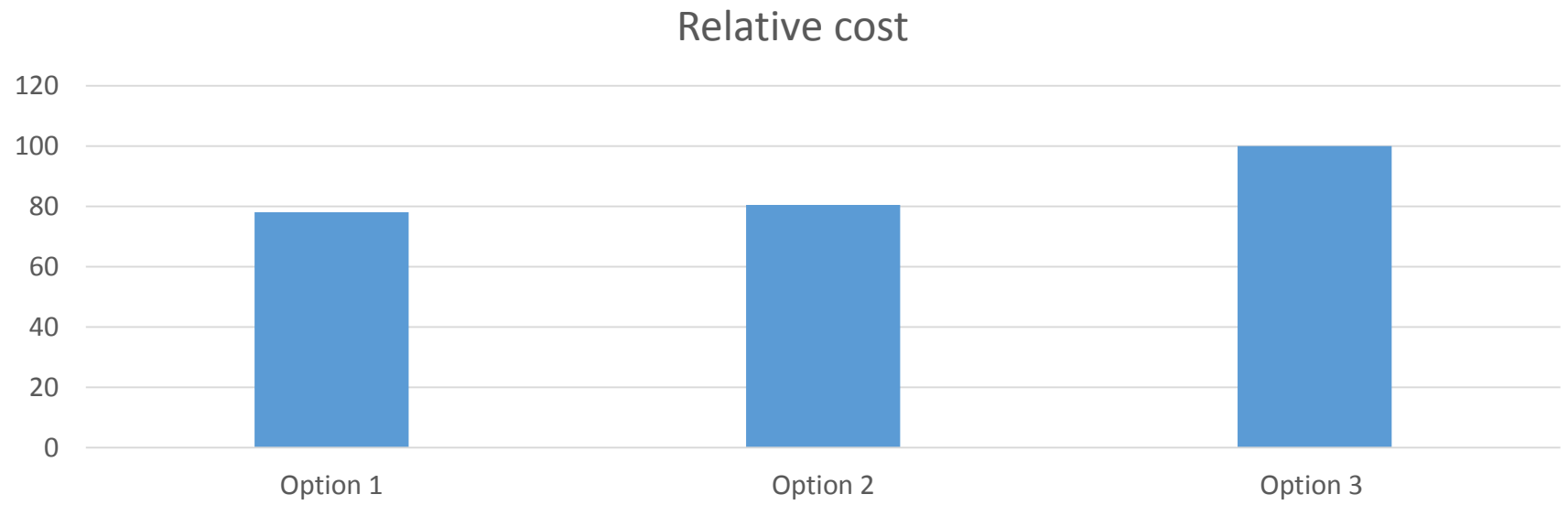
Uppsala high power system cost study

Based on actual prices from industry

Option 1:
1 x X-band 50 MW +PC
1 x X-band 8 MW
3 x S-band 6 MW + PC

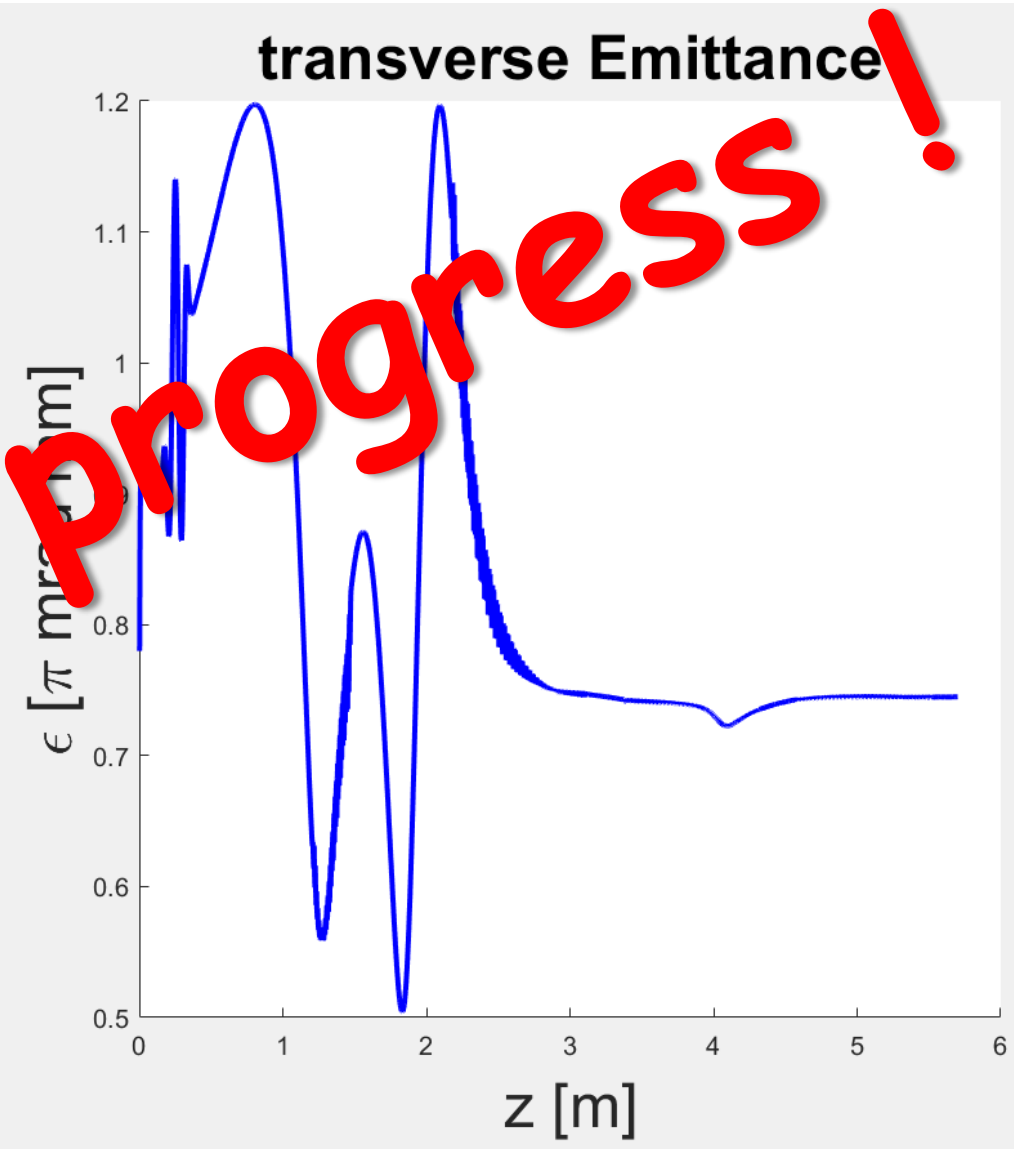
Option 2:
1 x X-band 50 MW +PC
1 x X-band 8 MW
1 x S-band 6 MW + PC
1 x S-band 45 MW

Option 3:
1 x X-band 50 MW +PC
1 x X-band 8 MW
3 x S-band 20 MW



Kevin Pepitone

Alternative design Design for run2



Work in progress !

nary
ptimum e-gun
:Light design",

S-Bar

Frequ

Peak

n. cell

Jordan is studying this configuration, promising results so far

Collaboration for high power RF system with Uppsala What is Uppsala doing

- Configuration study, what type of klystrons and modulators are optimum with respect to; cost, space, performance ?
- Define high power waveguide system, pulse compressor, circulator, loads, couplers
- Develop Solid state drive amplifier in s-band and x-band
- LLRF concept for amplitude and phase control based on μ-TCA technology, prototype
- Work on some control software
- Environmental studies on high voltage oils in the modulators and gas (SF6) in waveguides
- Put together an example turn-key system
  for example s-band mini klystron → deliver to CERN
- A number of documents to define the deliverables and specify LLRF are in the making

Kevin Pepitone