An Electron-Driven Neutron Source

Laurence Wroe (CERN, ATS-DO)
laurence.wroe@cern.ch

Steinar Stapnes, Walter Wuensch, Andrea Latina,
Roberto Corsini, Javier Olivares Herrados

CLIC Mini-Week 2023

Table of Contents

Table of Contents

VULCAN
(Versatile Ultra Compact Accelerator-driven Neutron source)

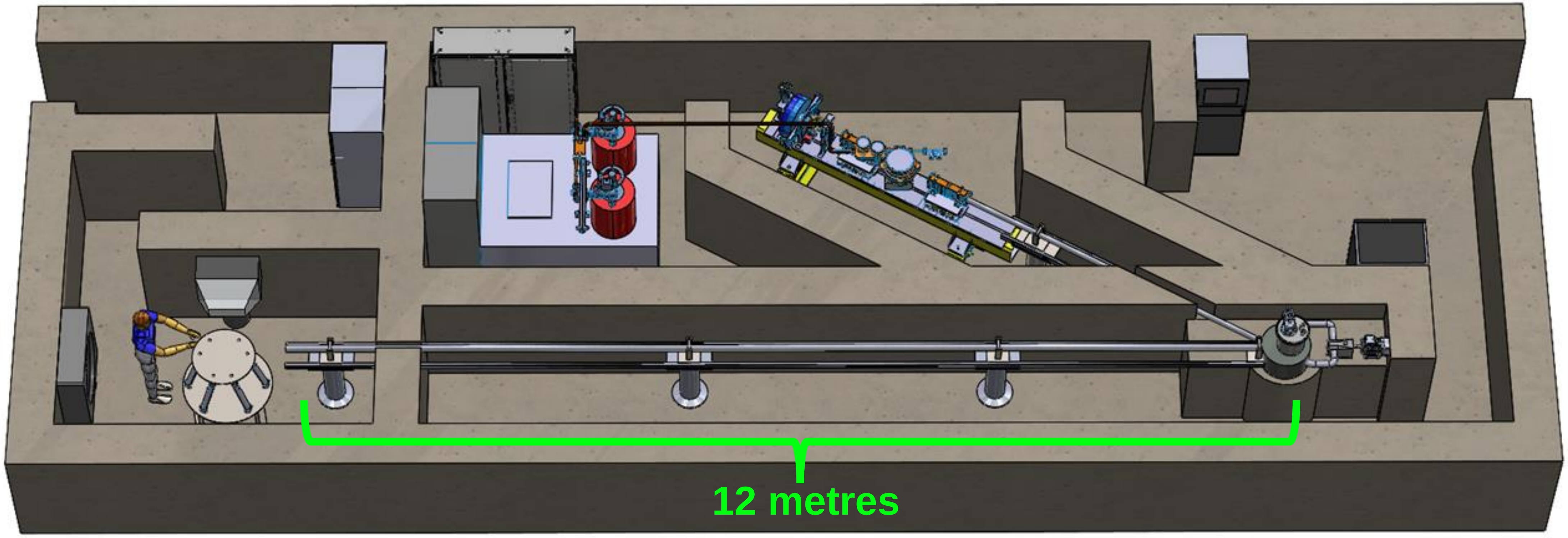
- **Turnkey solution** for generating **thermal neutrons (∽ Å)**
  - **Non-destructive, fast measurement** of **internal stresses** of bulk **metallic** and **ceramic** structures
  - **Non-destructive in-situ** and **in-operando diagnostic of electrodes** in electric batteries (measure the dendritic growth of lithium)

DAES
(Engineering solutions w/ neutron source expertise, Geneva)

DTI - Danish Technological Institute
(Neutron source instrumentation expertise, Denmark)

Xnovo Technology
(Software for instrumentation w/ x-ray crystallographic imaging expertise, Denmark)

VULCAN Conceptual Layout



- Small footprint (existing lab)
- Measurements in realistic times
- Operated by local staff
- Low maintenance
- Lower power but more specialised than large neutron facilities

CERN Funding

- **2 years of funding from CERN CIPEA grant to:**
  - Characterise the target-moderator-reflector system for generating neutrons in CERN’s CLEAR beamline
  - Develop conceptual design for compact and affordable electron linac optimized for VULCAN requirements

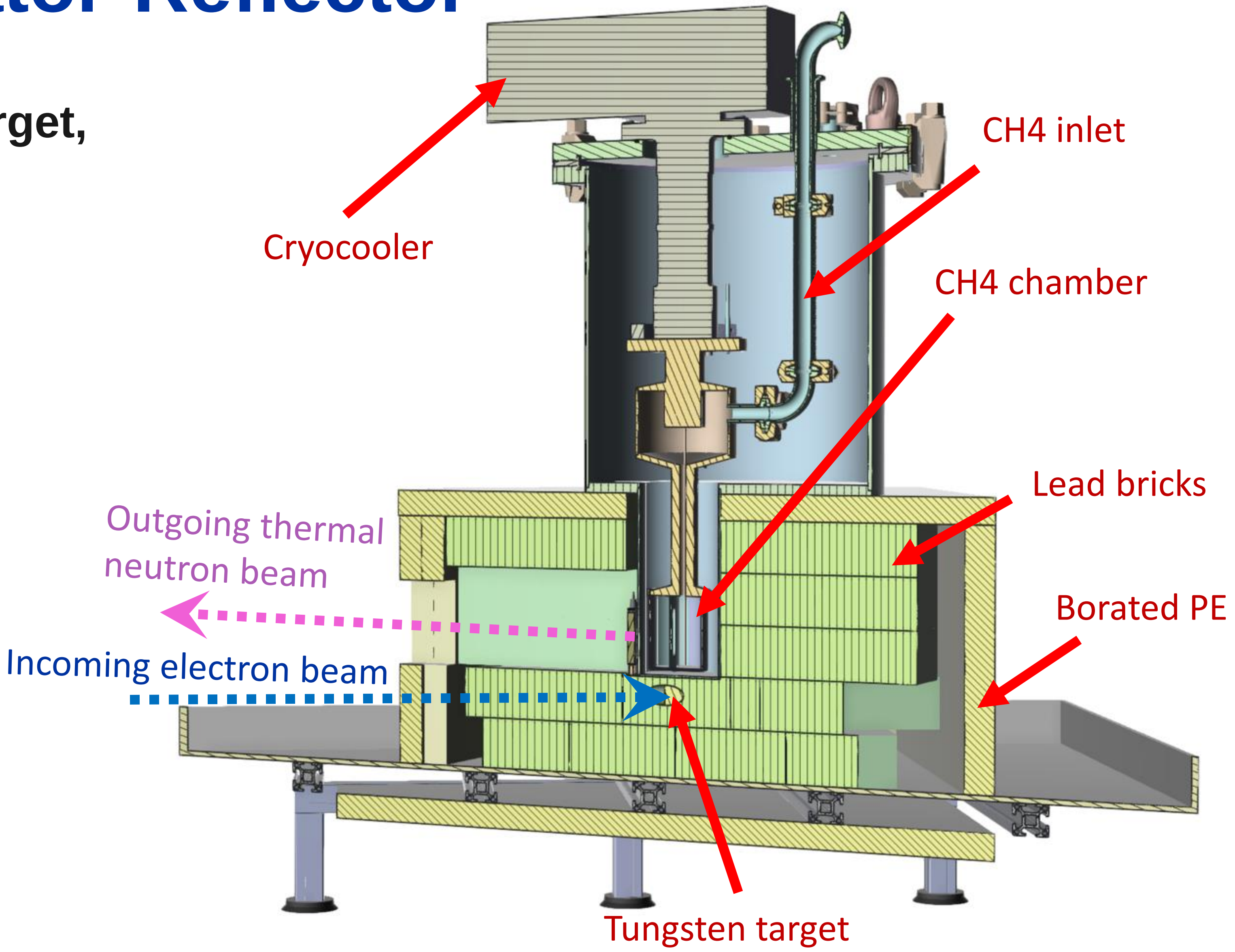
CIPEA

CERN Innovation Programme on Environmental Applications

Table of Contents

The Target-Moderator-Reflector

- **MeV e^- beam hits tungsten target, creating MeV *n***
- **MeV *n* moderated to meV *n*:**
  - Liquid CH4 - moderator
  - Lead bricks - reflector
  - Borated PE - absorber
- **Outgoing thermal *n* beam**
  - Speeds: ~ 1 km/s
  - Initial pulse width: < 20 µs
  - After 10 m, pulse width: ~ 5 ms



CLEAR Experiment

- **Measure neutron pulse flux and width at different distances**

- **Measurements with and without Gadolinium foils**

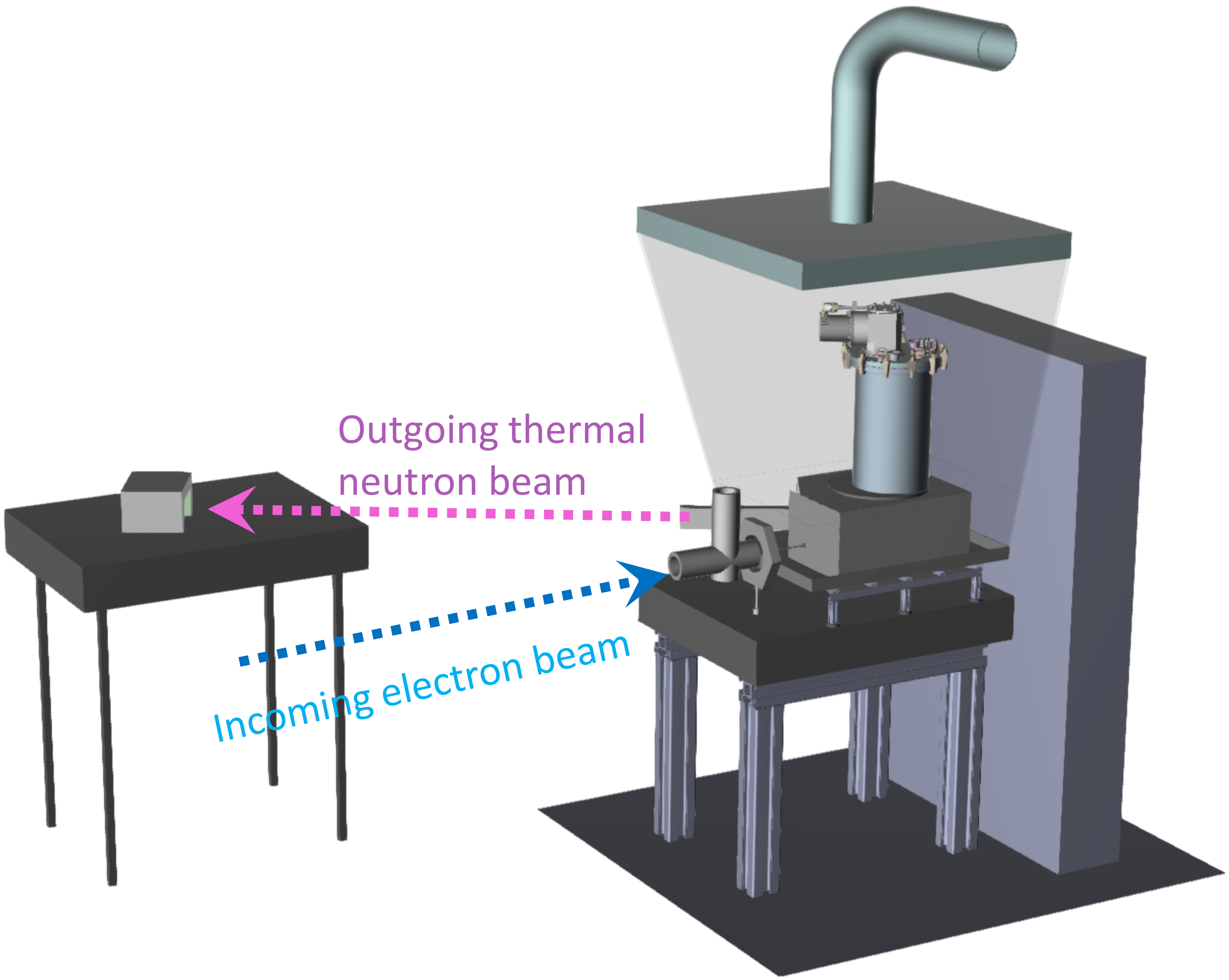


Table of Contents

What type of accelerator?

- **VULCAN requirements:**
  - Compactness
  - Affordability
  - Efficiency
  - Pulsed particle beam

High
Gradient
Electron
Linac
!!!

Beam Specification

Parameter	Value (at target)	Unit
Energy	35	MeV
Energy Spread	< 5	MeV
Beam Size	< 9	mm
e- Train Duration	< 1	µs
Repetition Rate	100	Hz
e- Train Charge (e- Beam Power)	Maximise (> 1)	nC kW
Facility Footprint	~ 15 x 5 x 2.5	m^3
Facility Cost	1-5	M€

Optimisation - High-Level Choices

- **Cost, compactness and charge heavily dependent on:**
  - Frequency choice (S-, C- or X-band - vary)
  - RF source (Single Klystron - vary power, set by market)
  - Accelerating structure (Choose TW - < 1 µs, pulse compressor)
  - Injector (Choose thermionic)
- **Assume other ancillaries (diagnostics, vacuum system, correctors, cooling + HVAC etc.) are a constant cost**

Optimisation Process Step 1: RF

RF structure FoMs (f, R, Q, v_g)

RF Klystron (t_k, P)

Pulse Compressor (f, t_k, t_t, t_f, Q)

↓

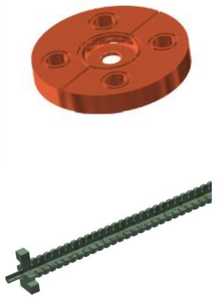
Vary accelerating structure number of cells (N) and train length (t_t)

↓

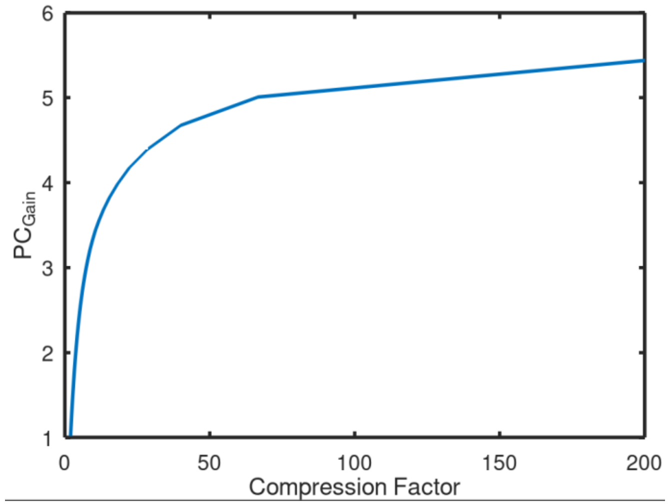
Calculate maximum charge accelerated
Limited by either beam loading or maximum klystron power

Example: XLS based structure

Parameter	Units	Value
Frequency	GHz	11.994
Phase advance per cell	rad	$2\pi/3$
Average iris radius a	mm	3.5
Iris radius a	mm	4.3-2.7
Iris thickness t	mm	2.0-2.24
Number of cells per structure		109
Accelerating cell length	mm	8.332
Structure length L_s	m	0.9
Group velocity v_g/c	%	4.7-0.9
Filling time t_f	ns	146



Parameters	Unit	Target	Simulation
RF Frequency	GHz	-	11.9942
Peak RF power	MW	≥6	6.4



RF structure FoMs (f, R, Q, v_g)

RF Klystron (t_k, P)

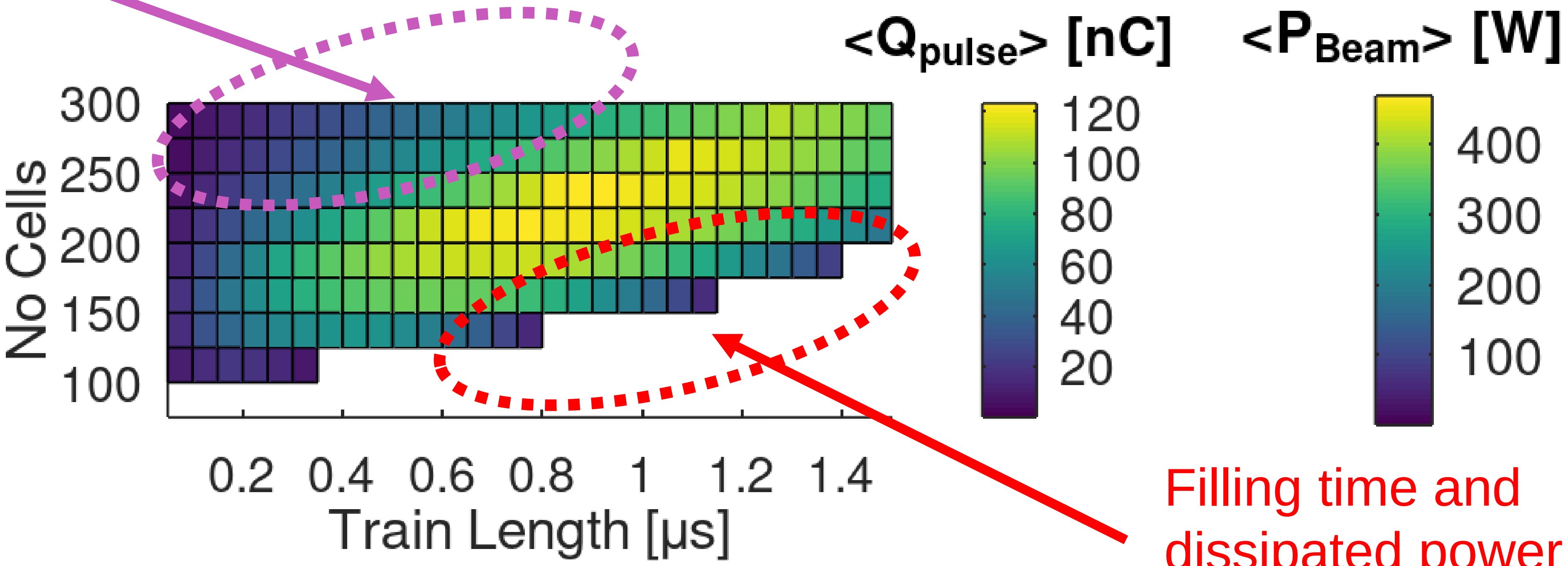
Pulse Compressor (f, t_p, t_t, t_f, Q)

Vary accelerating structure number of cells (N) and train length (t_t)

Example: XLS based structure

Calculate maximum charge accelerated
Limited by either beam loading or maximum klystron power

Beam loading too high



Filling time and dissipated power too high

Optimisation Process Step 2: Beam Dynamics

Take optimum number of cells and train length

↓

Incorporate bunching cells and use RF_Track to optimize them for transport and energy

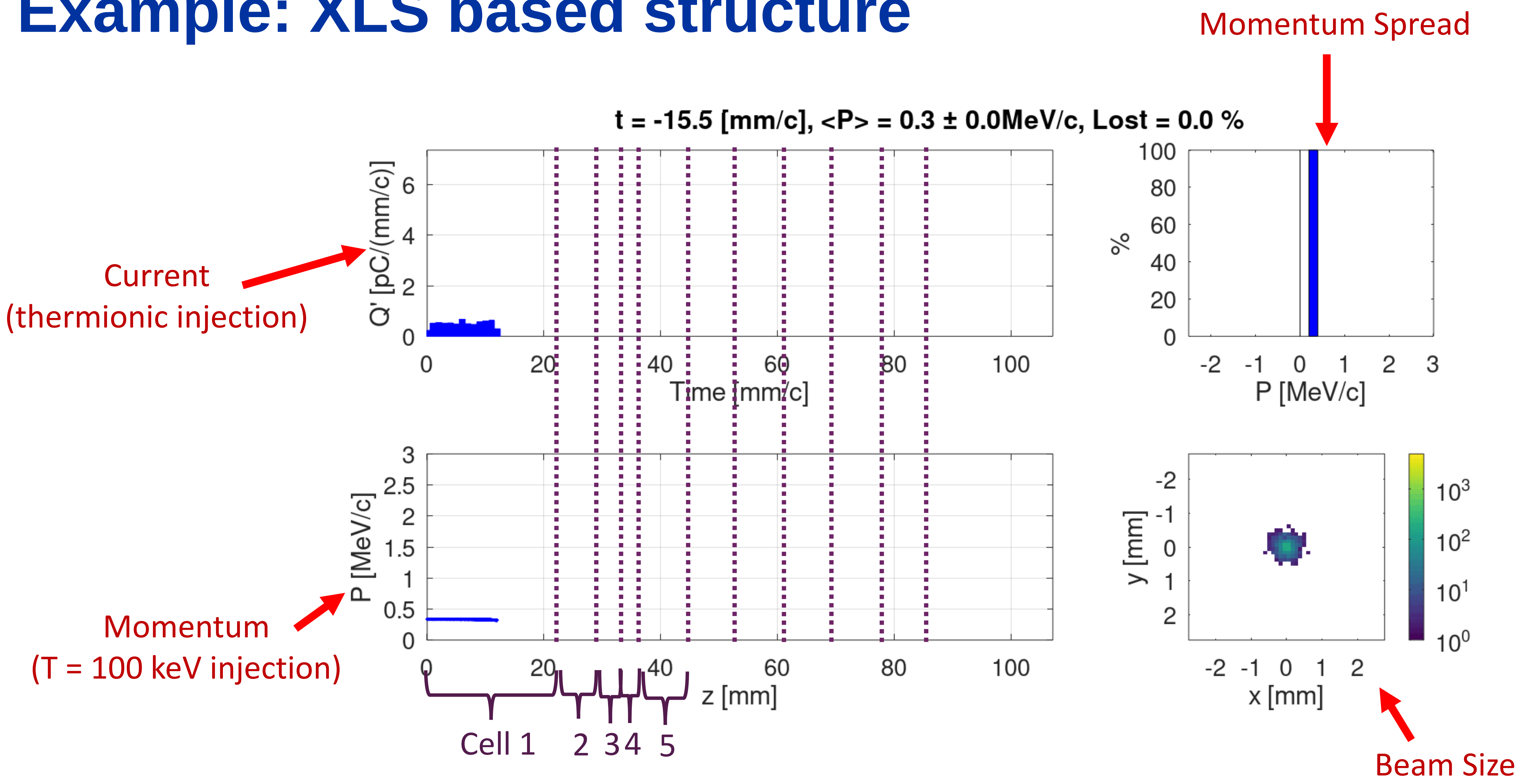
↓

Refine structure to compensate for bunching cells and iterate above

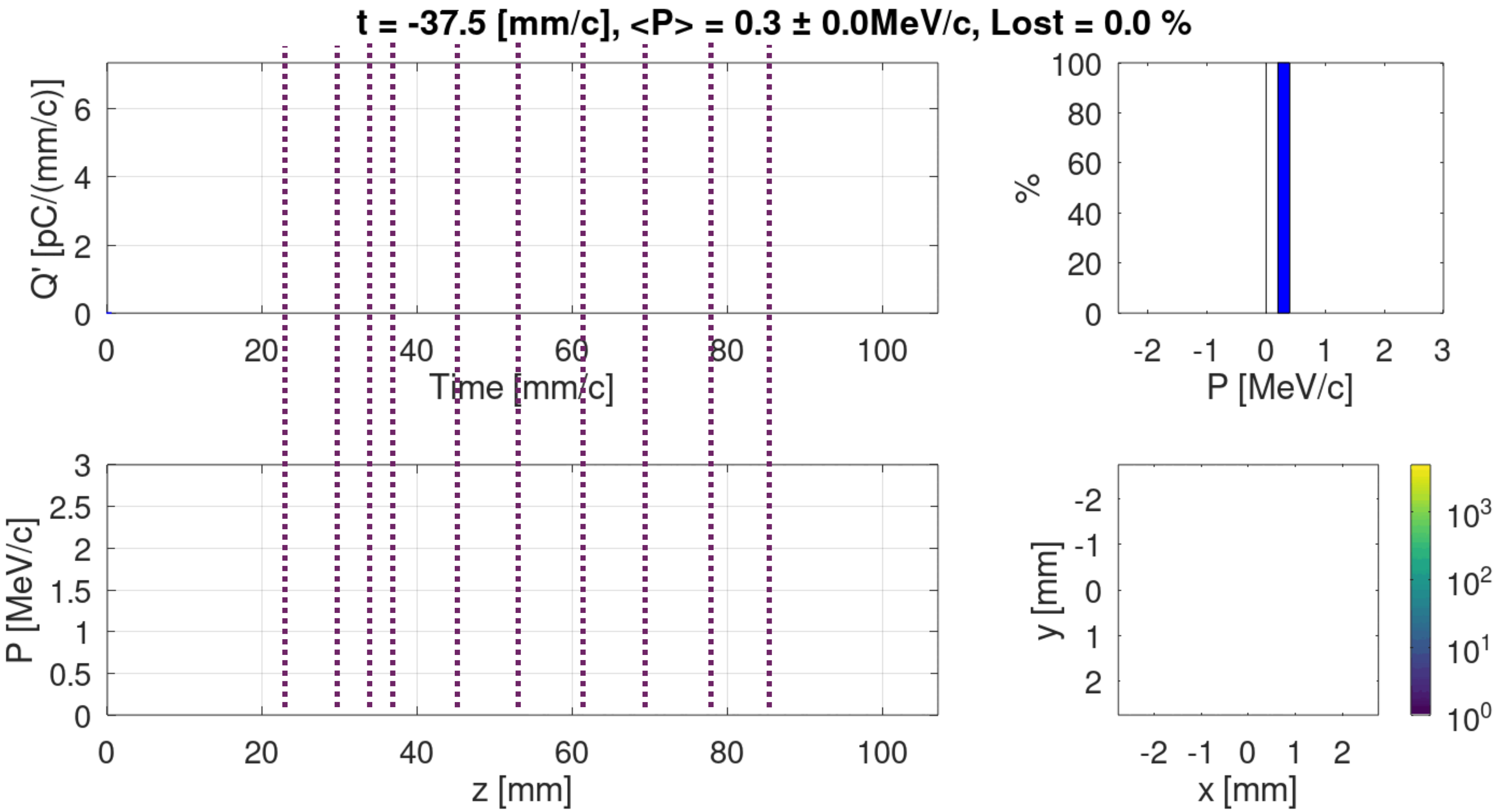
↓

Complete start-to-end simulation from gun to target
(Include space charge, wakefield, misalignments effects)

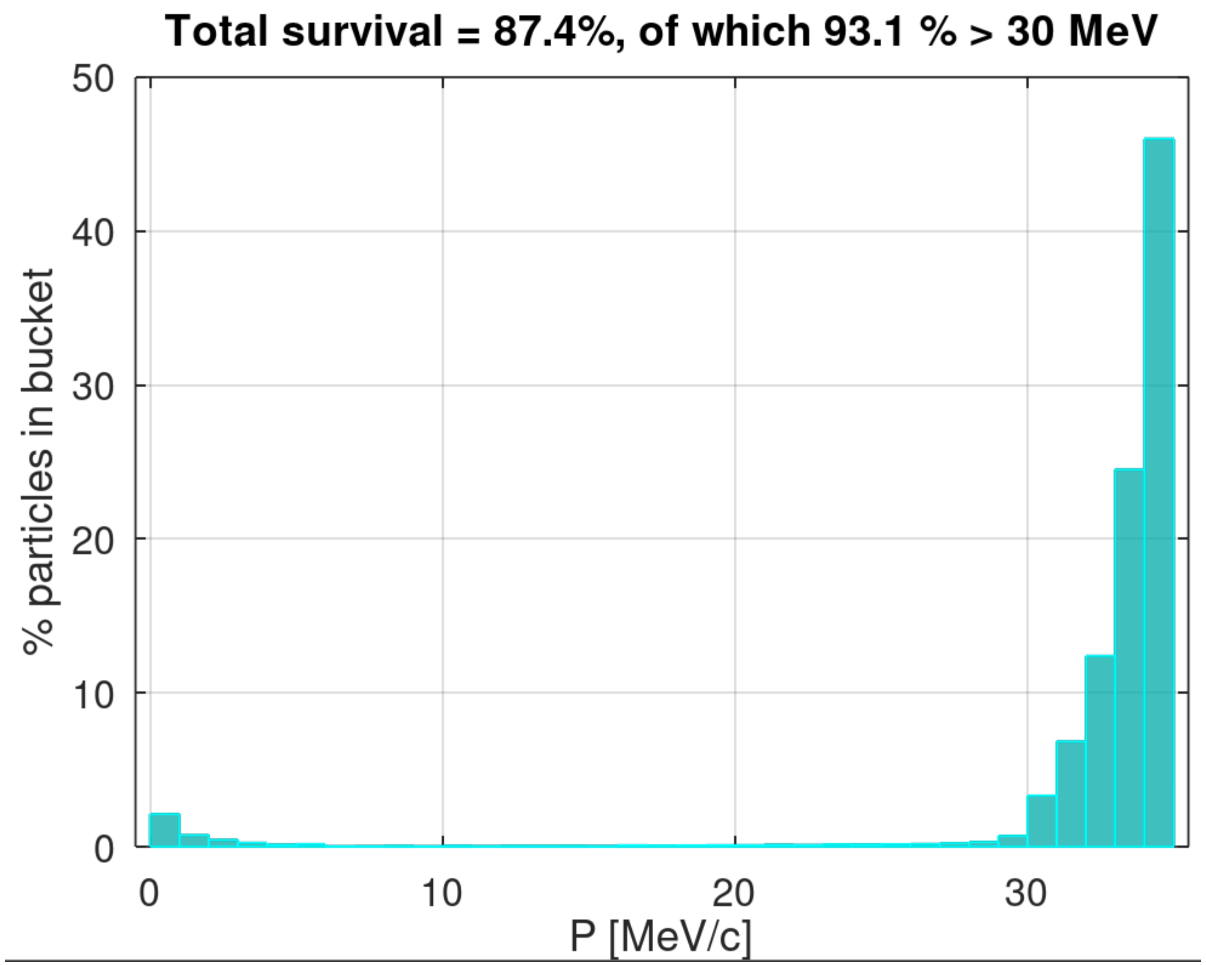
Example: XLS based structure



Example: XLS based structure



Example: XLS based structure



DELIVERED TO TARGET

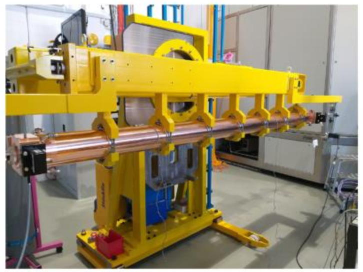
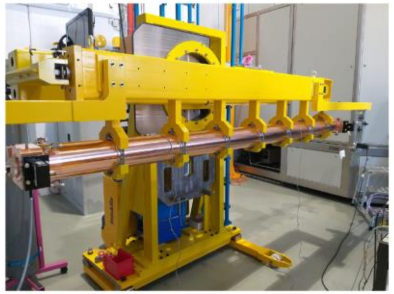
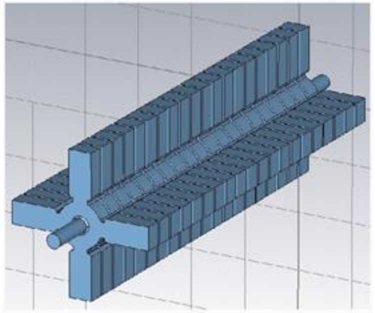
- 120 nC charge in 700 ns

  (Average beam power of 400 W)

- σ_f ~ 1 mm
- > 90 % particles over 30 MeV

Table of Contents

Technologies Compared

X-Band TW (XLS)	X-Band TW (XLS)	S-Band TW (FERMI HG)	S-Band TW (FERMI HG)	C-Band TW (ELI)
		 Fig. 3. HG1 structure on the holder during bead pull test with a wire passing through beam pipe.	 Fig. 3. HG1 structure on the holder during bead pull test with a wire passing through beam pipe.	
https://www.compactlight.eu/	https://www.compactlight.eu/	https://www.sciencedirect.com/science/article/pii/S0168900223005338	https://www.sciencedirect.com/science/article/pii/S0168900223005338	https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.20.032004
Canon E37113 X-band Klystron:	**CPI VKX-8255A X-band Klystron:**	**Canon E37325 S-band Klystron:**	**… S-band Klystron:**	**… C-band Klystron:**
• **5 μs pulse**	• **3.5 μs pulse**	• **5 μs pulse**	• **5 μs pulse**	• **4 μs pulse**
• **8 MW power**	• **25 MW power**	• **10 MW power**	• **25 MW power**	• **8 MW power**

	X-Band TW (XLS)	X-Band TW (XLS)	S-Band TW (FERMI HG)	S-Band TW (FERMI HG)	C-Band TW (ELI)
RF					
Struct Length [m]	**1.7**	**1.0**	**3.3**	**2.3**	**3.0**
Klystron Power [MW]	**8**	**25**	**10**	**25**	**8**
Loaded <G> [MV/m]	23	37	11	18	12
> 30 MeV [%]	93	-	83	80	-
BEAM					
Train Charge [nC] **Beam power [W]**	**120** **390**	**650** **2450**	**220** **780**	**1100** **3500**	**100** **390**
Train Length [ns]	700	1000	800	1000	950
Bunch Charge [pC]	15	-	140	360	-
Beam Size [mm]	0.9	-	2.7	2.8	-
Peak Current [mA]	220	-	420	2200	-
COST					
Cost Estimate	**1.5 M€**	**1.8 M€**	**1.4 M€**	**1.8 M€**	**1.5 M€**

Table of Contents

Conclusions and Next Steps

- **Preliminary study**
  - Select technology to develop into CDR design with DAES
    - Optimum trade-off between cost, compactness and electron beam power
  - Write code into user-friendly tool
  - Write up results
- **Developing to mini-CDR**
  - Develop RF structure
    - CST simulations
  - Develop beam dynamics
    - Wakefield and offset studies
  - Write into mini-CDR

Thanks for listening

CLIC Mini-Week 2023

Baseline cost estimate

- **Assume the below costs are constant across the different technology choices**
  - Gun + Cathode + HV supply = 75 k€
  - RF distribution network (inc. LLRF) = 190 k€
  - Mechanics and controls = 25 k€
  - Vacuum equipment = 40k€
  - Diagnostics = 140 k€
- **TOTAL BASELINE = 455 k€**
- **(Note infrastructure, electrical installation, controls ignored here)**