ESSnuSB – A NEUTRINO SUPER BEAM FROM THE ESS LINAC

Mamad Eshraqi for ESSnuSB

Beam physics section leader / Accelerator Division / ESS
ESSnuSB Linac upgrade WP leader

ESSnuSB has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 777419

ESS

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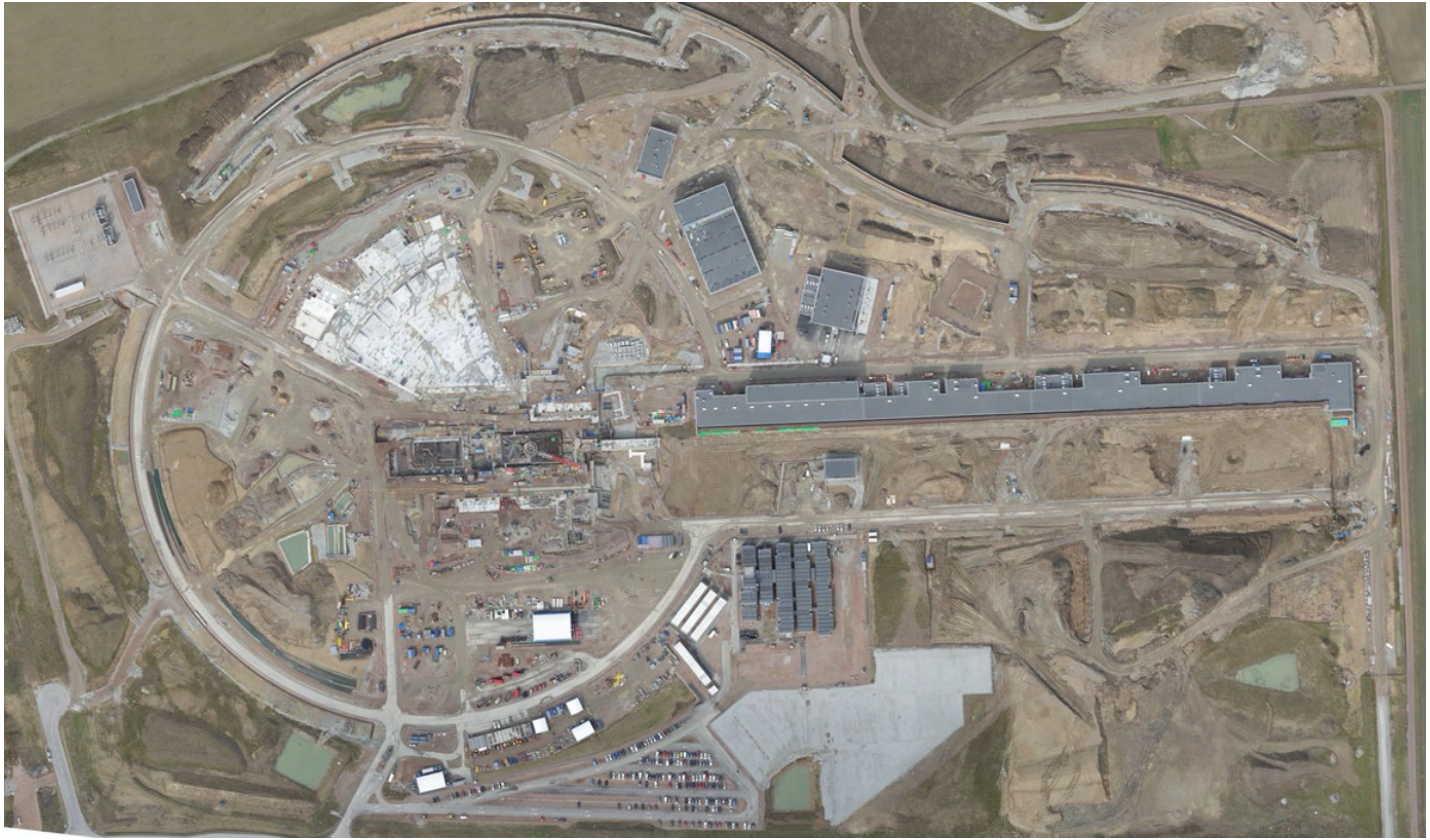
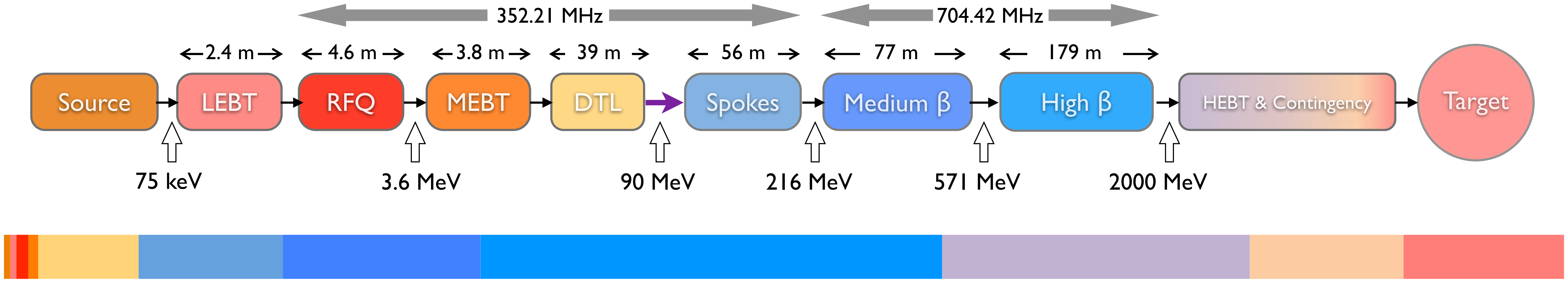


2017 April

ESS

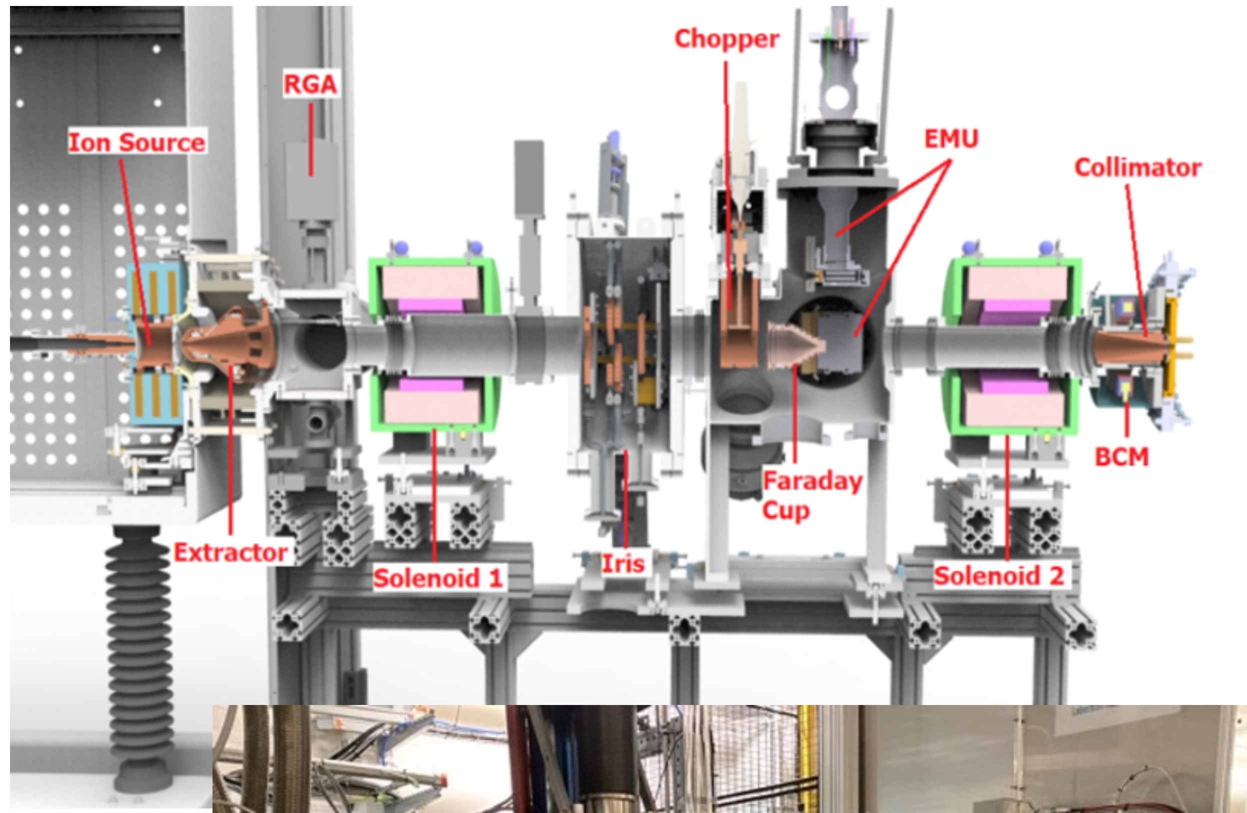
2021 Nov

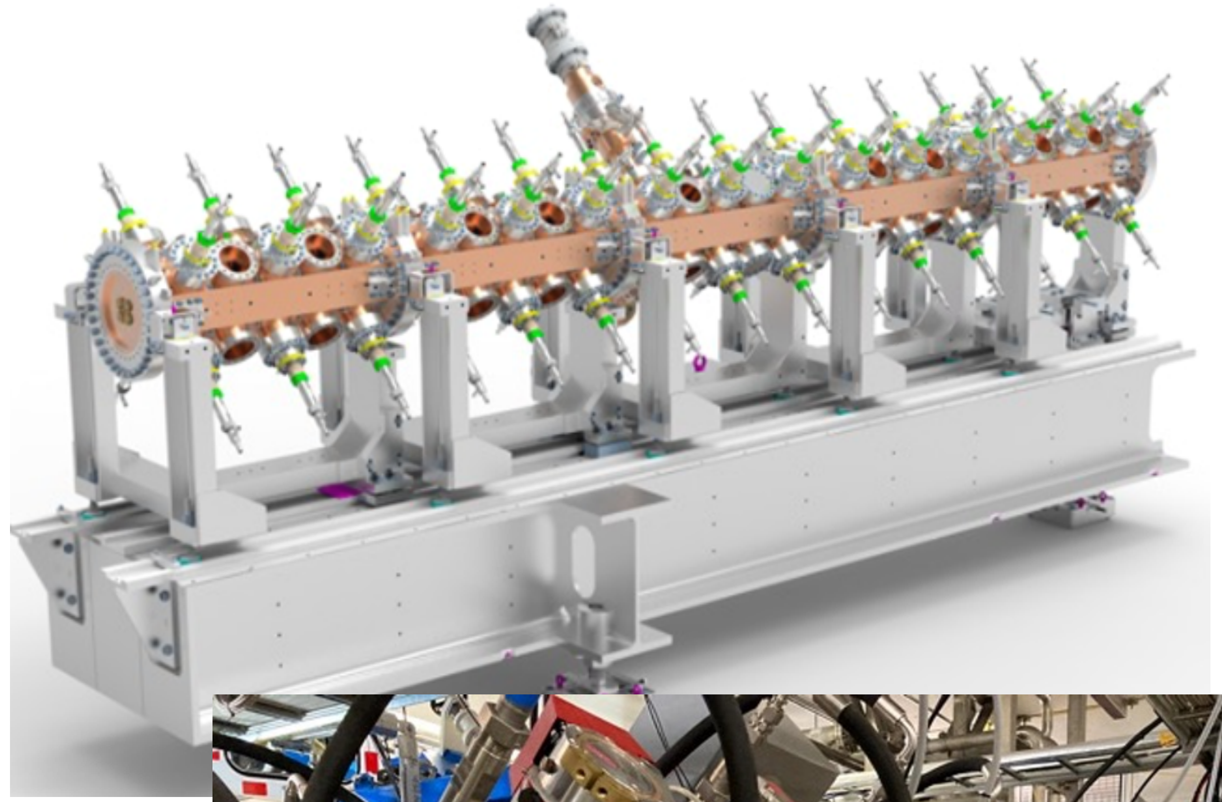
ESS LINAC

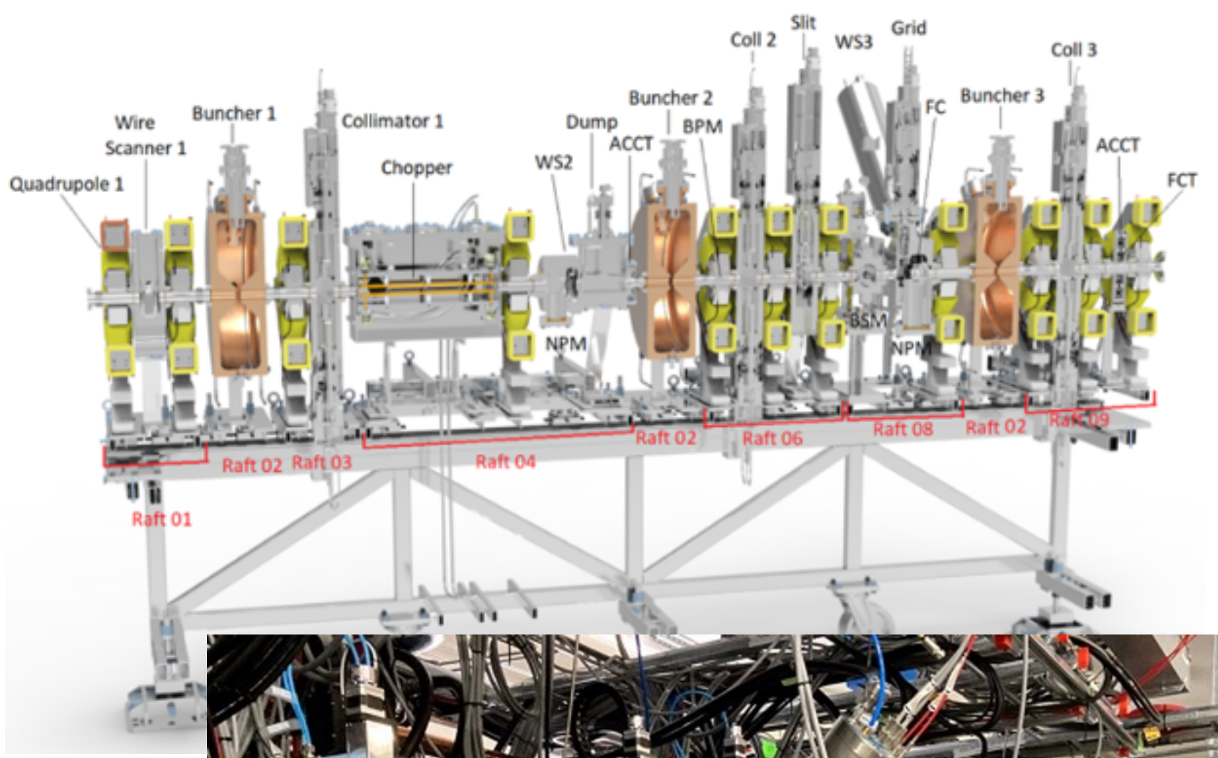


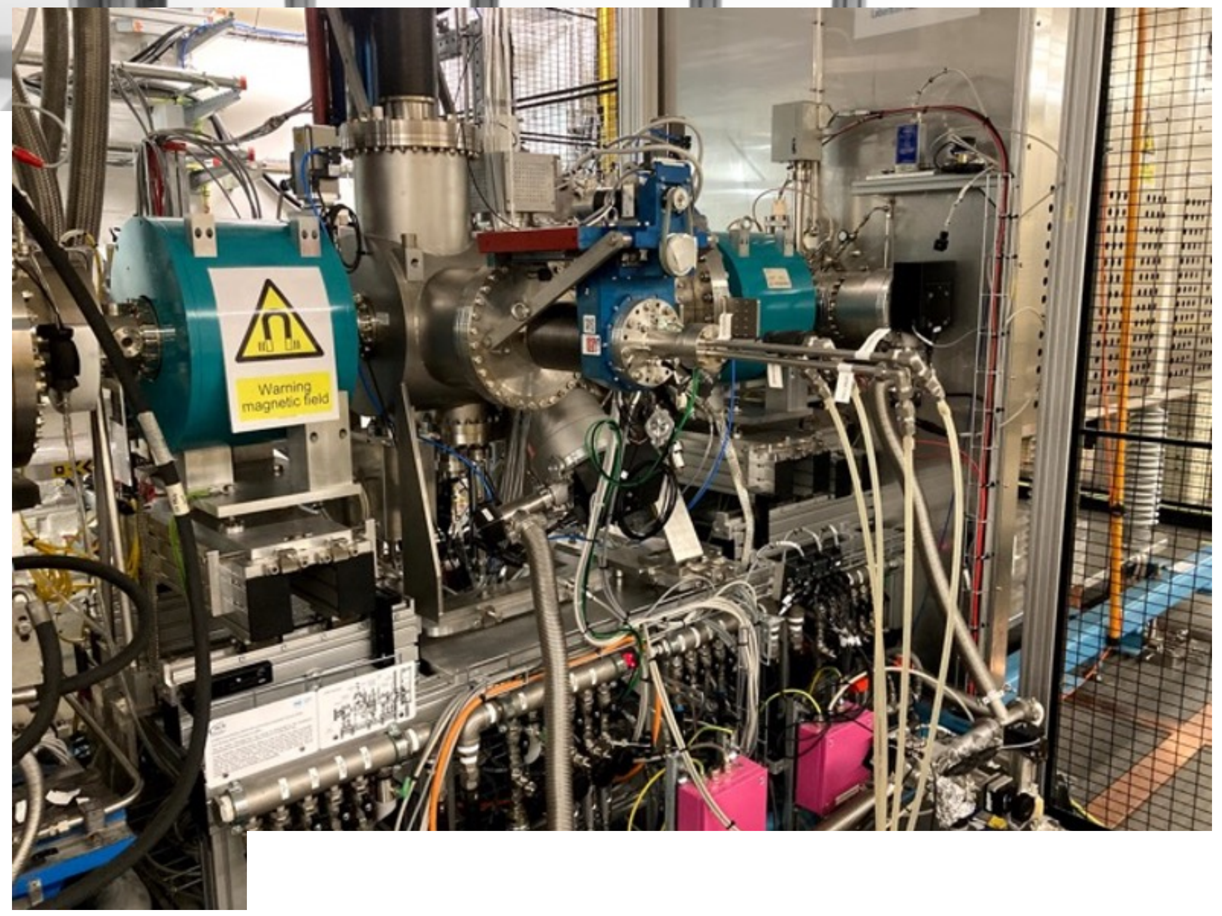
	Length (m)	W_in (MeV)	F (MHz)	β Geometric	No. Sections	T (K)
LEBT	2.38	0.075	--	--	1	~300
RFQ	4.6	0.075	352.21	--	1	~300
MEBT	3.81	3.62	352.21	--	1	~300
DTL	38.9	3.62	352.21	--	5	~300
LEDP + Spoke	55.9	89.8	352.21	0.50 (Optimum)	13	~2
Medium Beta	76.7	216.3	704.42	0.67	9	~2
High Beta	178.9	571.5	704.42	0.86	21	~2
Contingency	119.3	2000	704.42	(0.86)	14	~300 / ~2

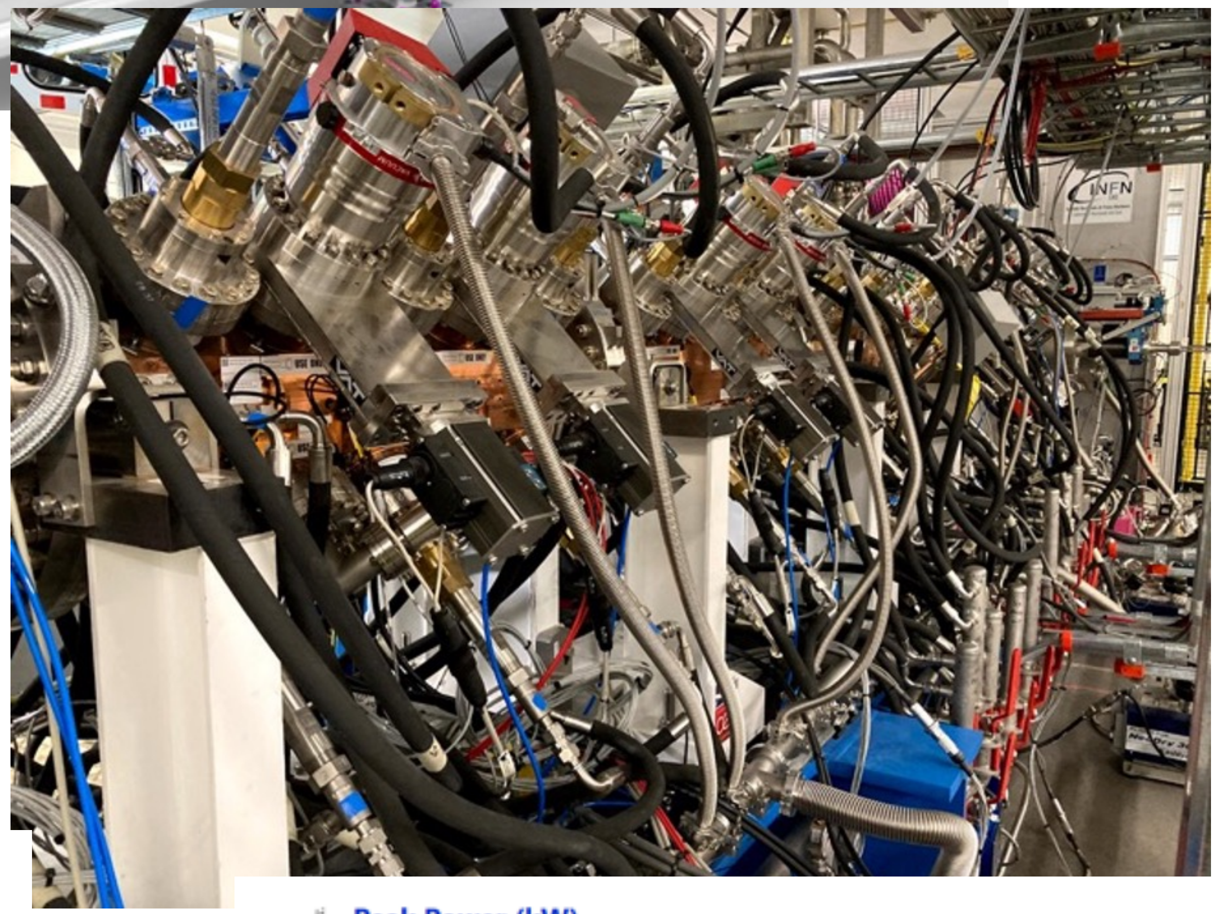
NCL – DTL

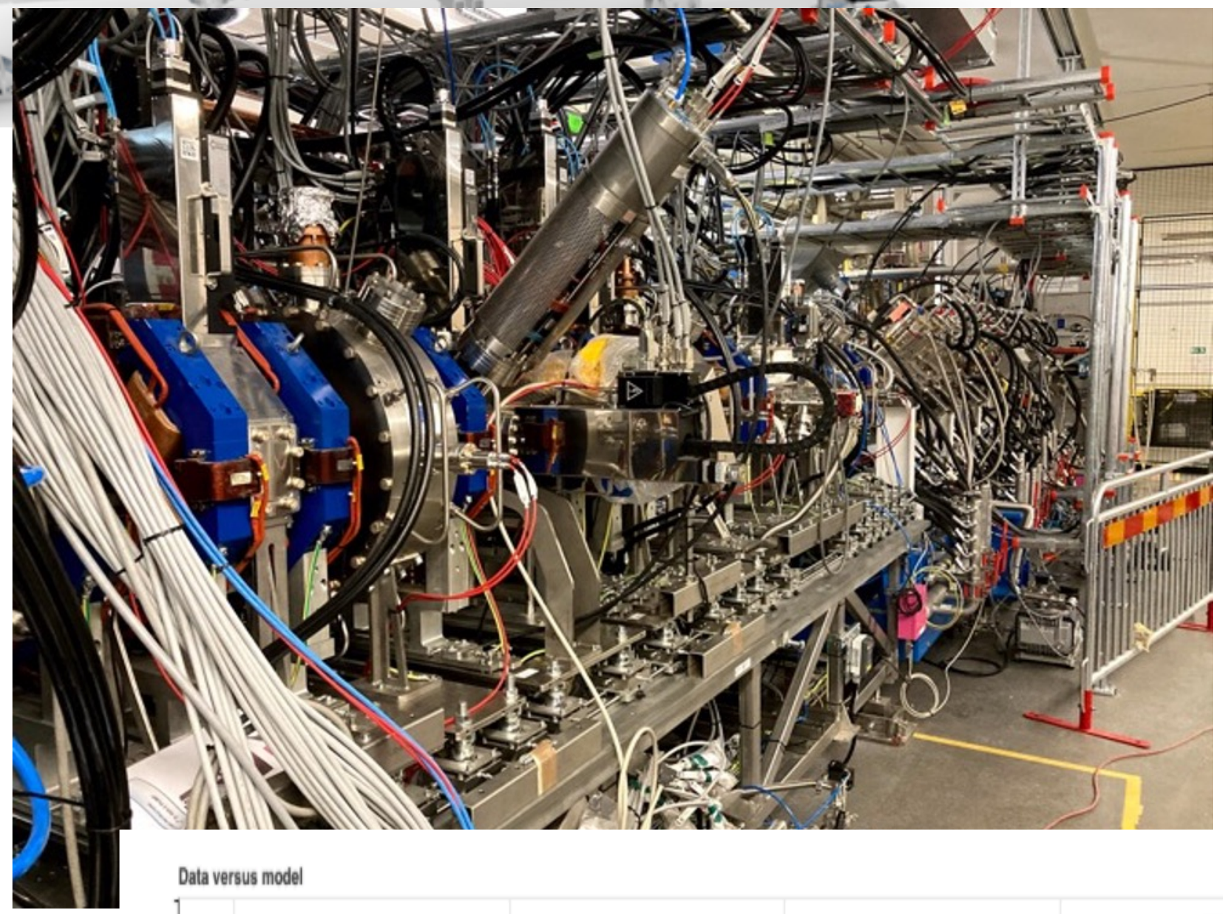


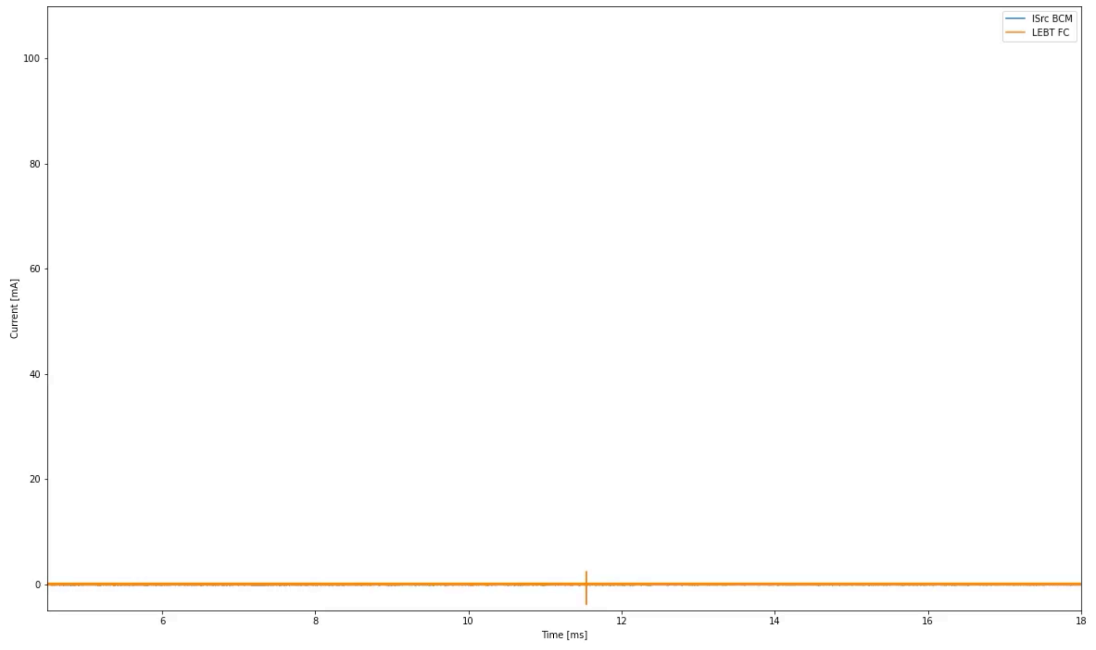


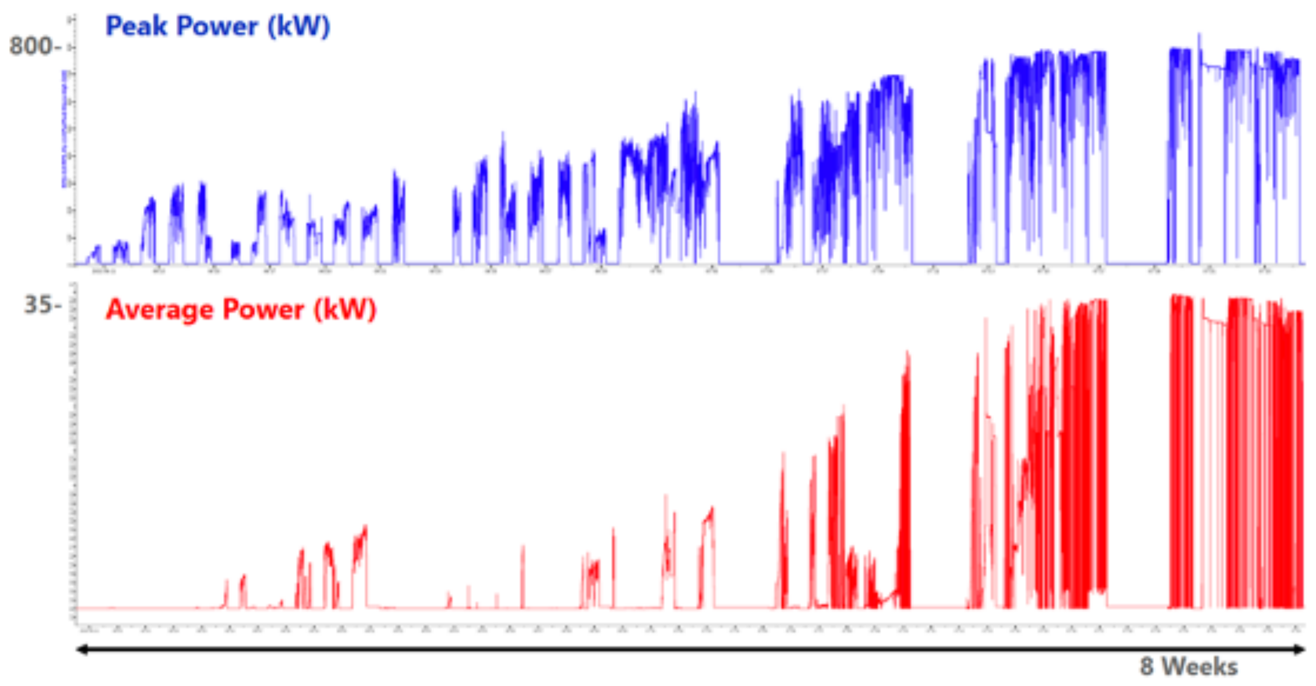


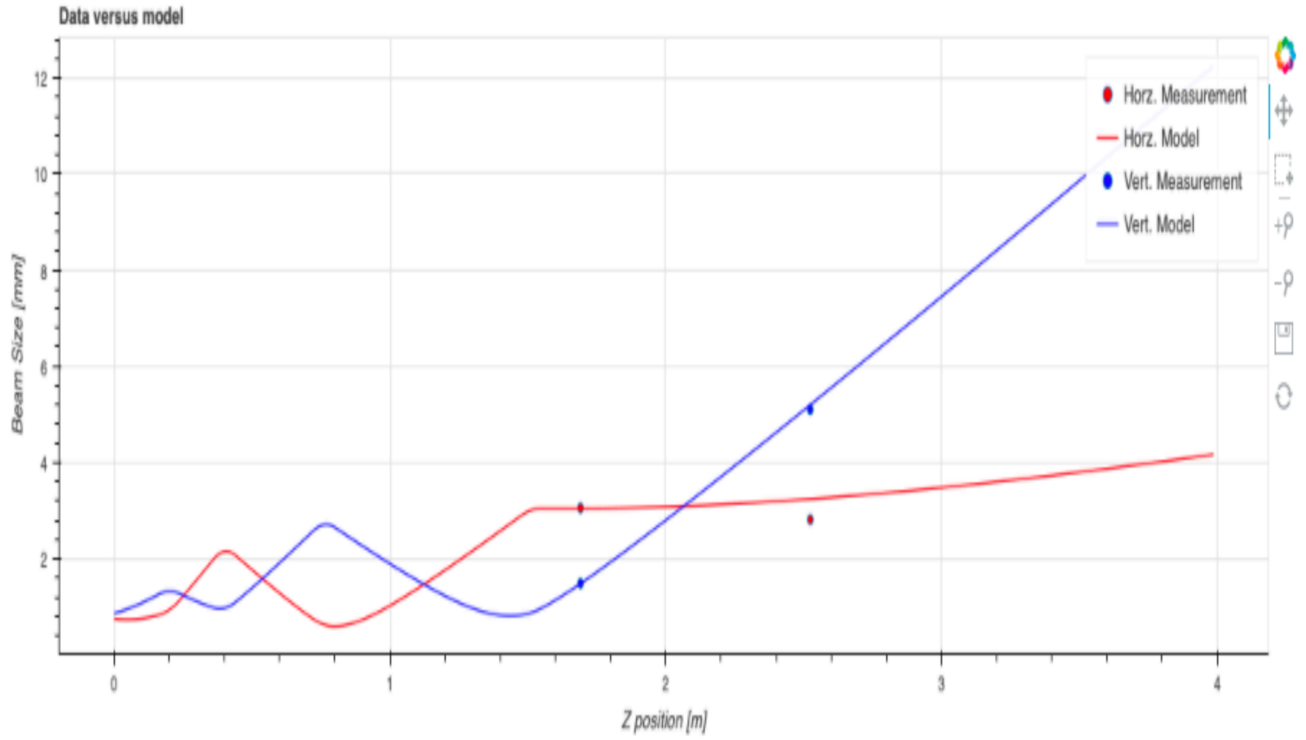








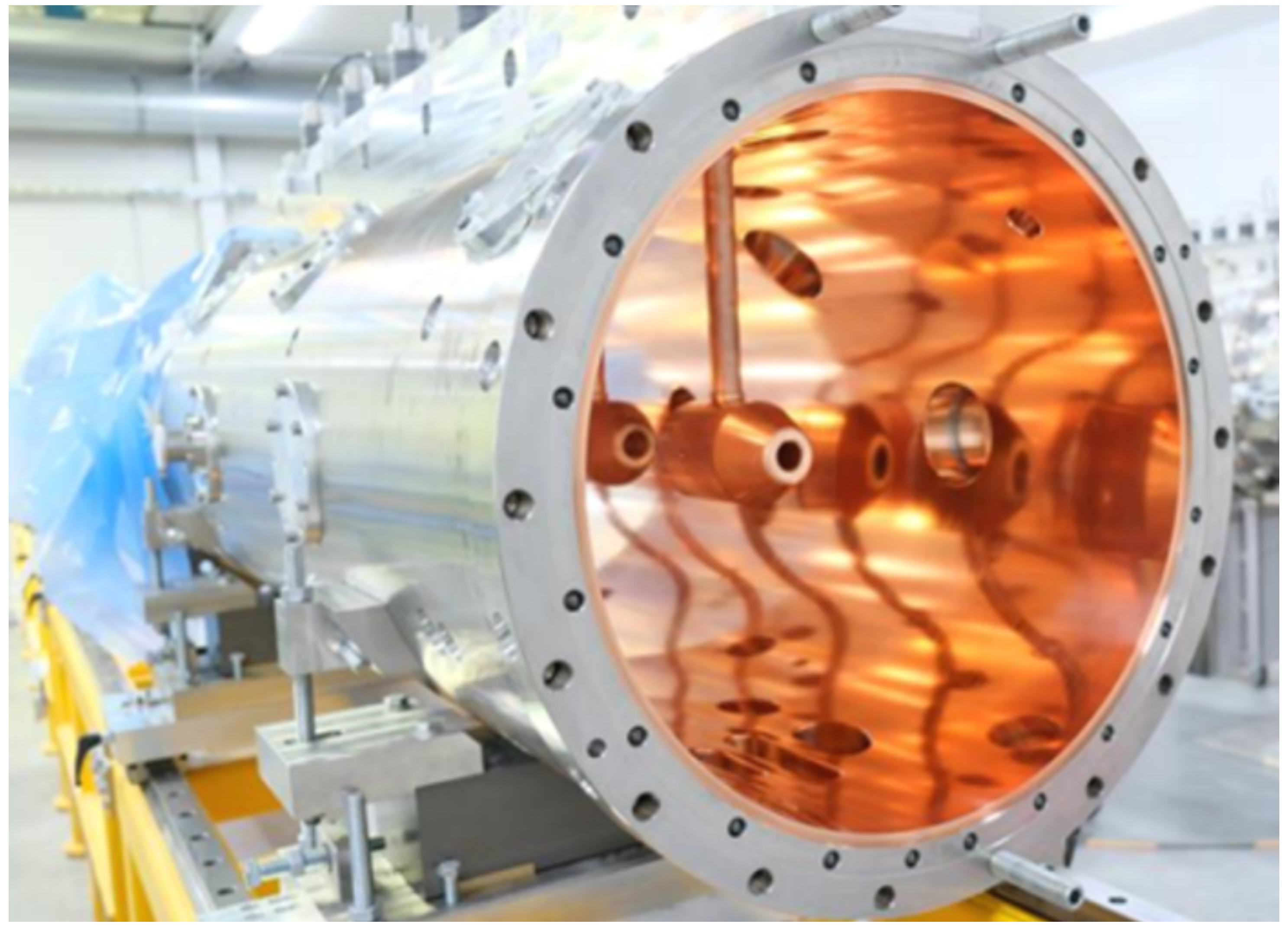




Ciprian Plostinar et al (2020-2021)

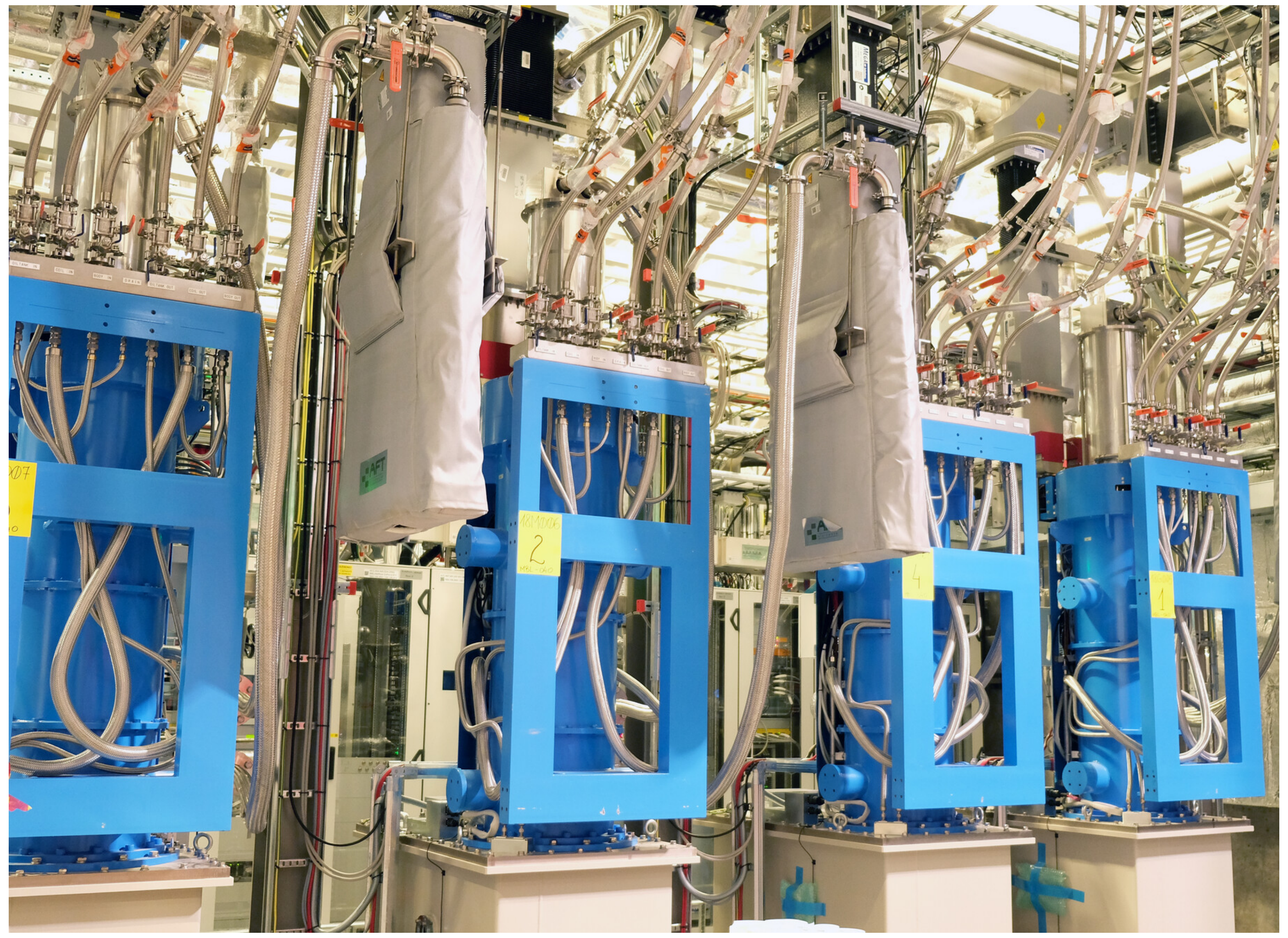
DTL

- DTL1 tuning concluded with a field flatness of <2% and a tilt sensitivity of <100%/MHz

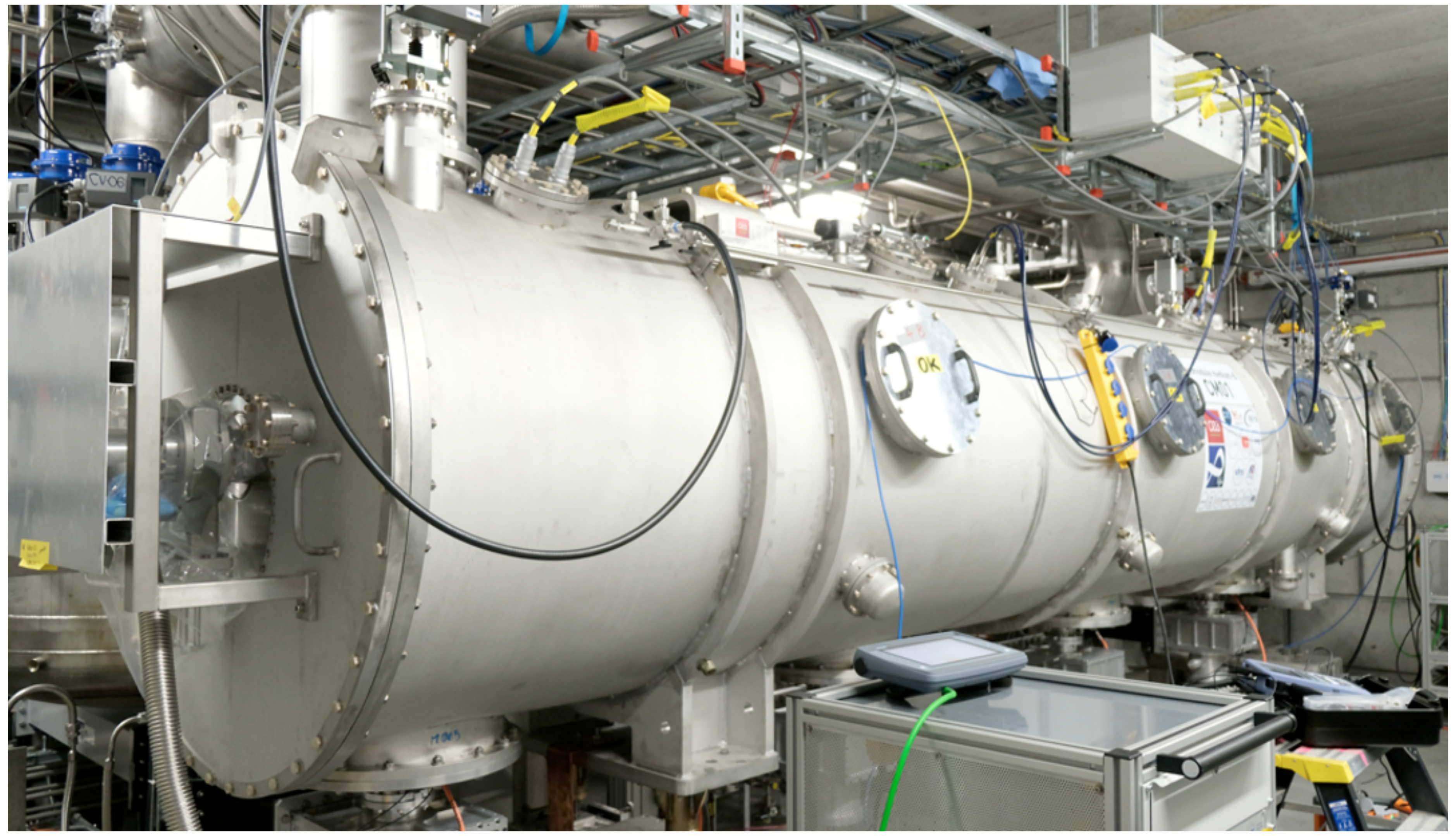


Ciprian Plostinar (2021)

SCL

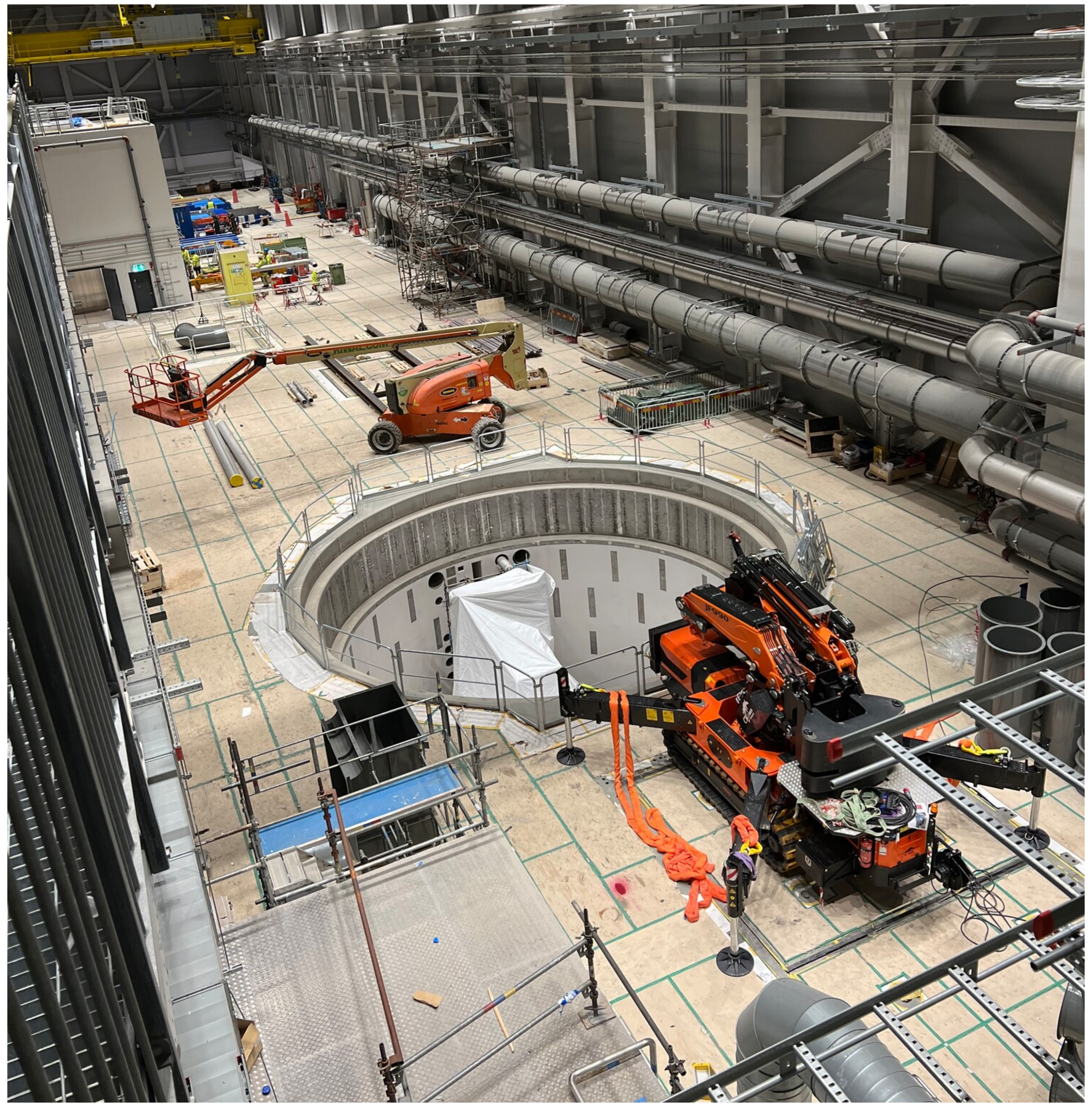


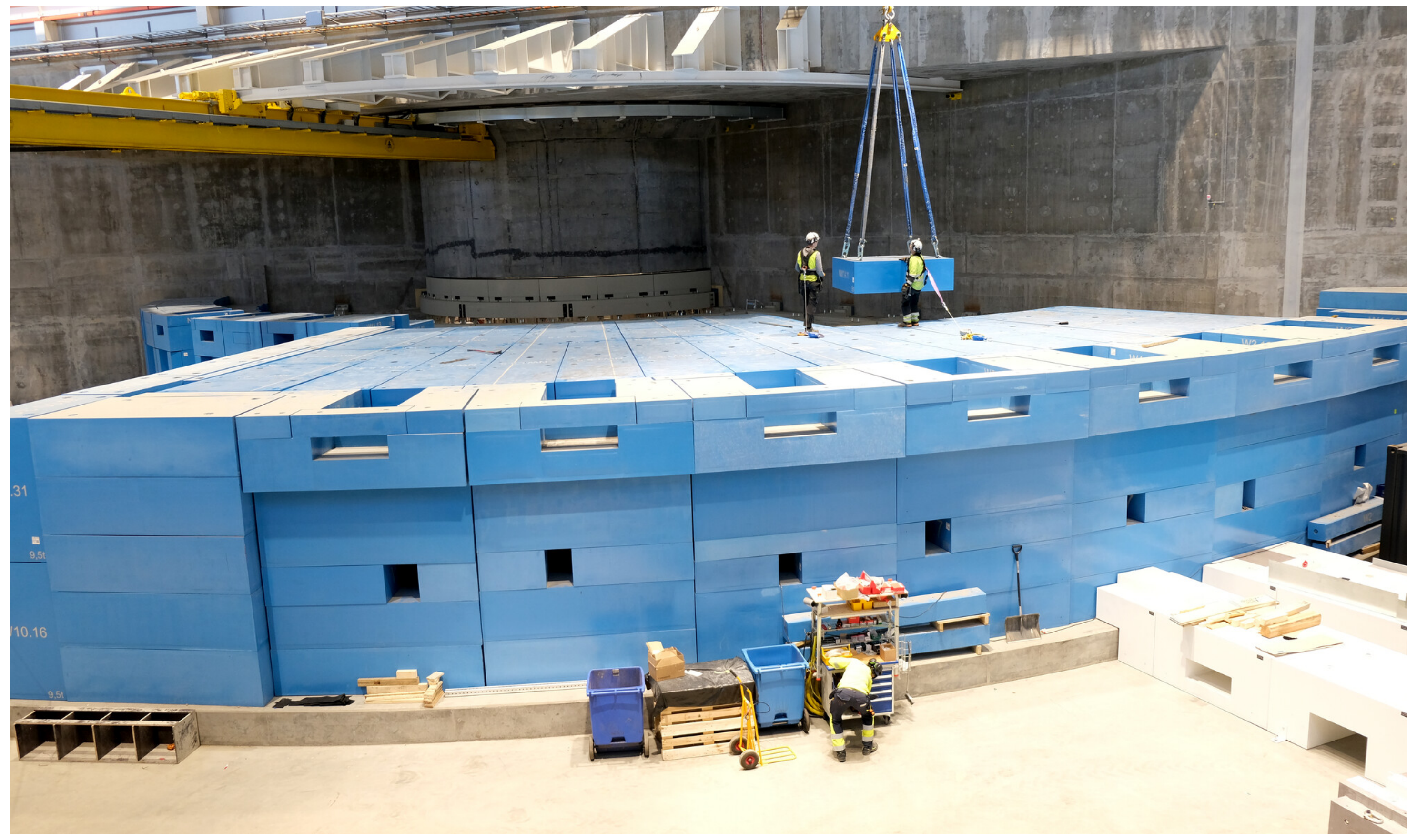





Mats Lindroos, Ciprian Plostinar (2021-2022)

Target, Instrument hall





Ulrika Hammarlund (2020-2022)

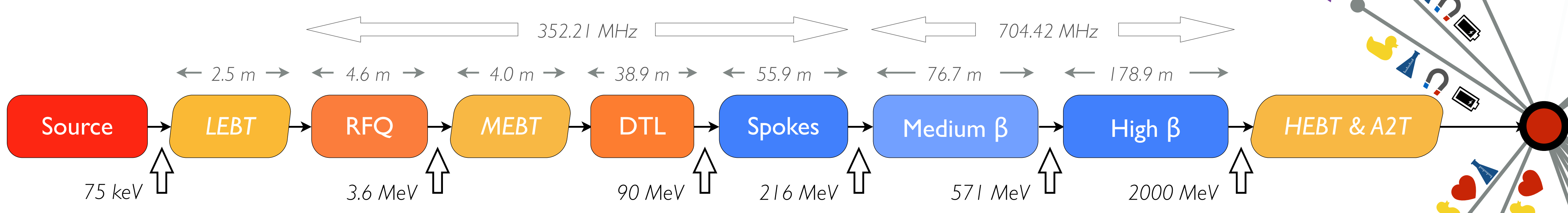
ALMOST ALL ESS IN ONE SLIDE

Key Linac parameters

Energy	2.0 GeV
Current	62.5 mA
Repetition rate	14 Hz
Pulse length	2.86 ms
Losses	<1W/m
Ions	p

Flexible/Upgradable design

Minimize energy consumption



Controls

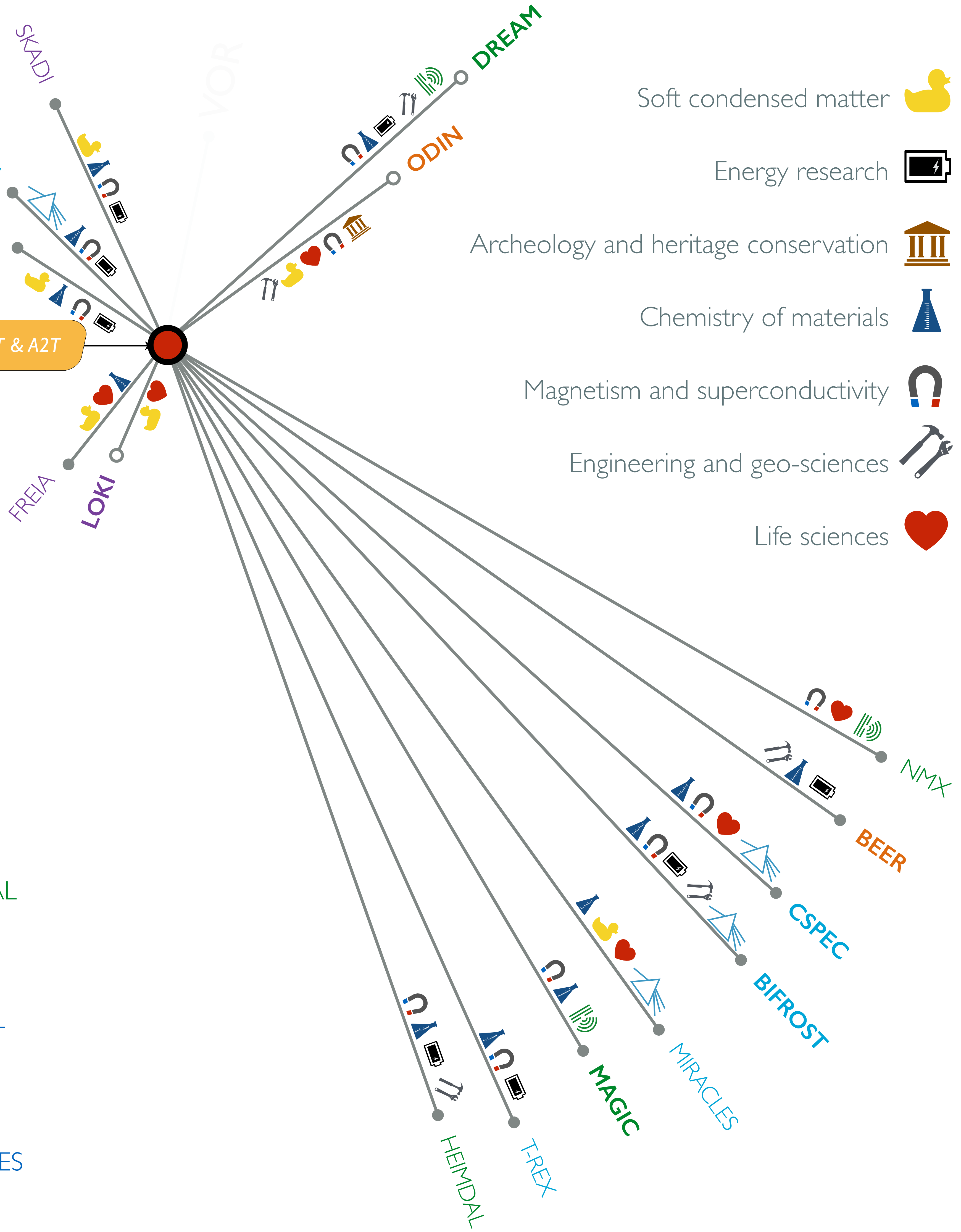
Control variables.	~1.6E6 PVs
MPS and PSS	
EPICS7	
μTCA.4	

Rotating tungsten target

Target diameter	2.6 (0.45) m
Mass	11 (3) tons
	36 sectors
Rev. freq.	~0.4 Hz
Expected lifetime	5 years
Cooling	He gas
Beam ports	42
Peak flux	~30-100 x ILL
Cold moderator	Liquid H_2
	17 K
	30 mm
Thermal moderator	H_2O
	300 K
	30 mm

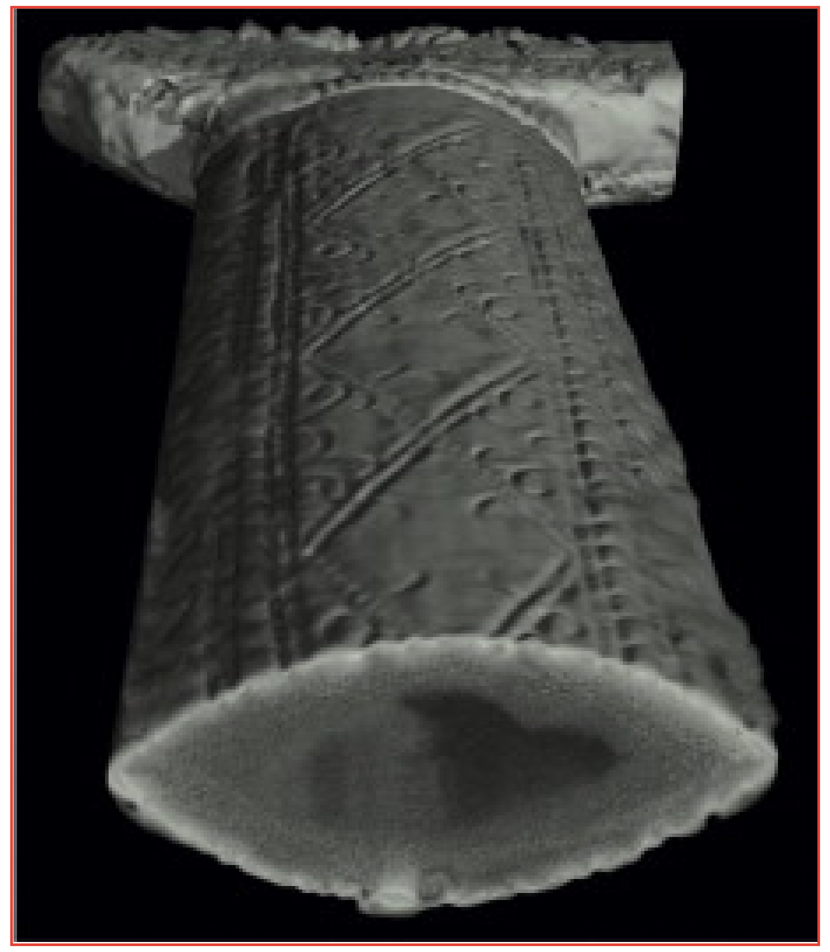
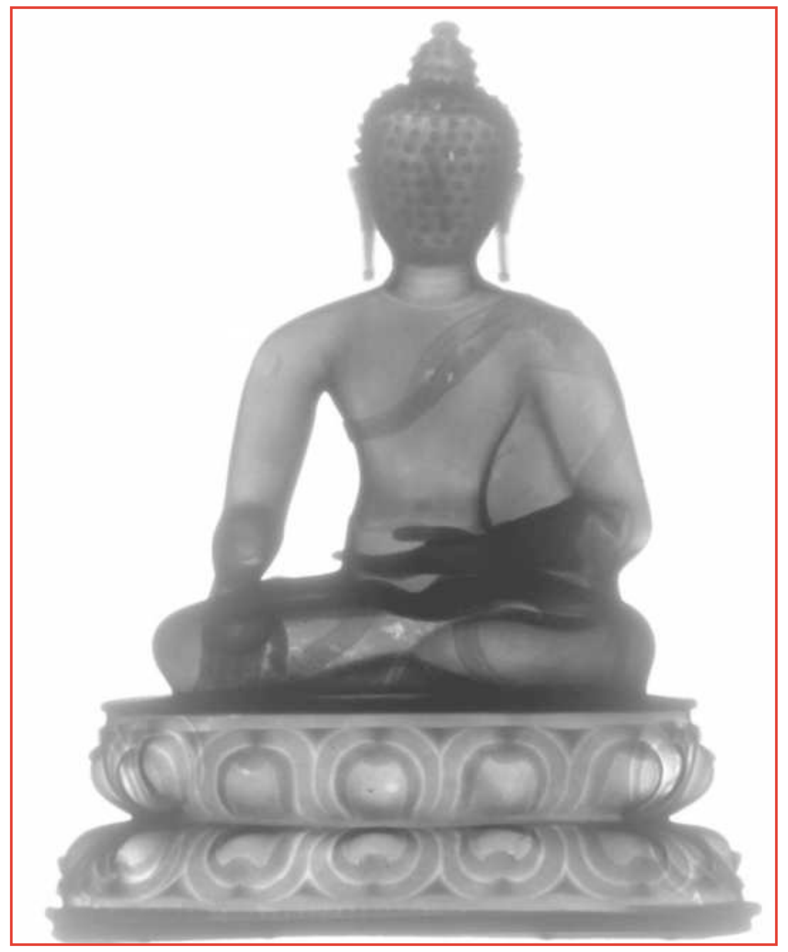
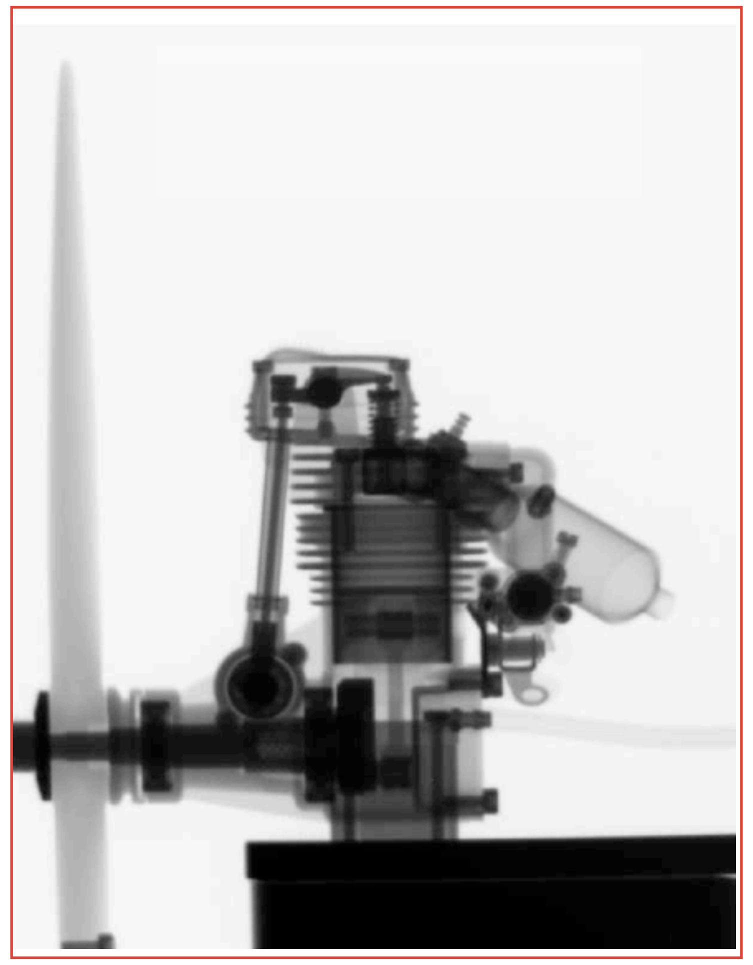
Instruments

∞ Large Scale Structures	LOKI, SKADI, ESTIA, FREIA
Engineering	BEER, ODIN
Diffraction	NMX, DREAM, HEIMDAL, MAGIC
Spectroscopy	C-SPEC, BIFROST, T-REX, VESPA, MIRACLES

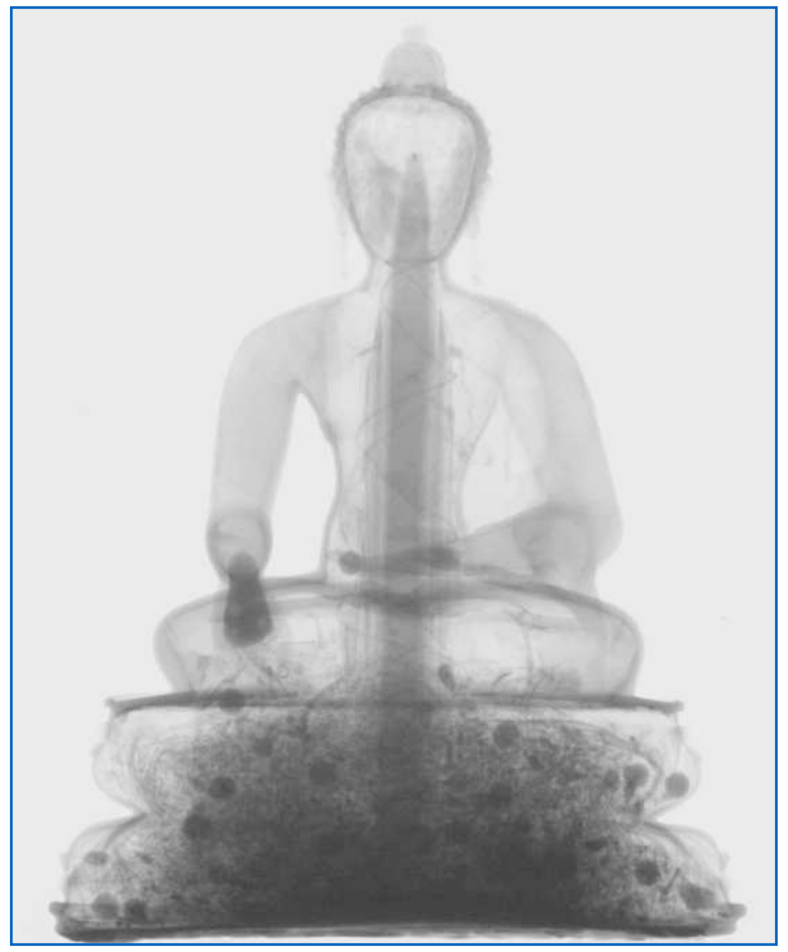
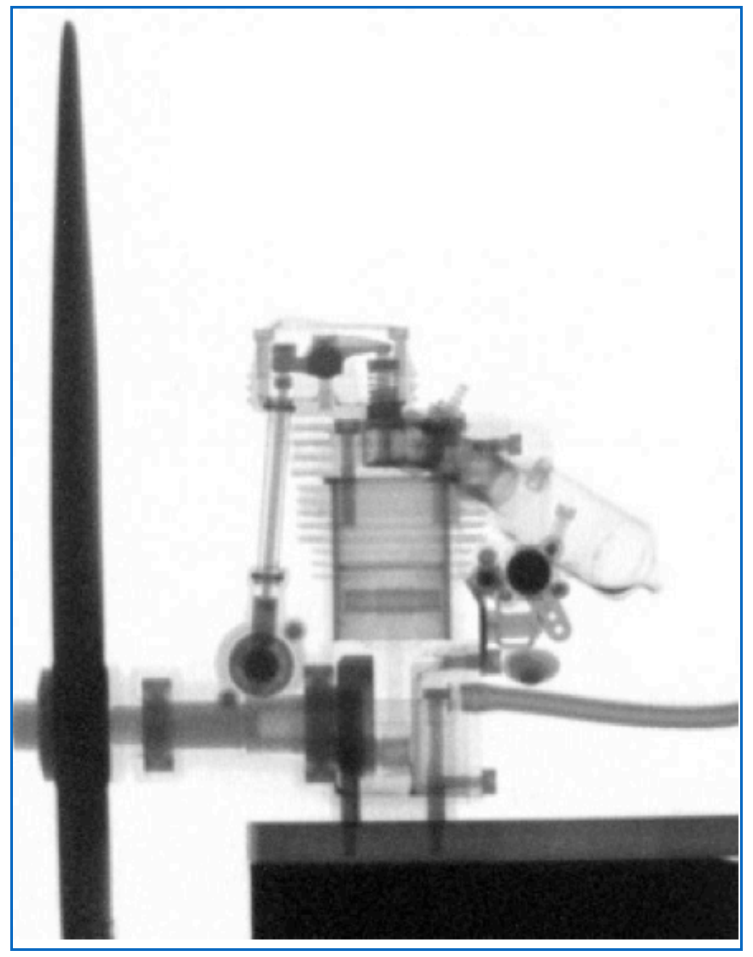


Photons vs. Neutrons

X-rays

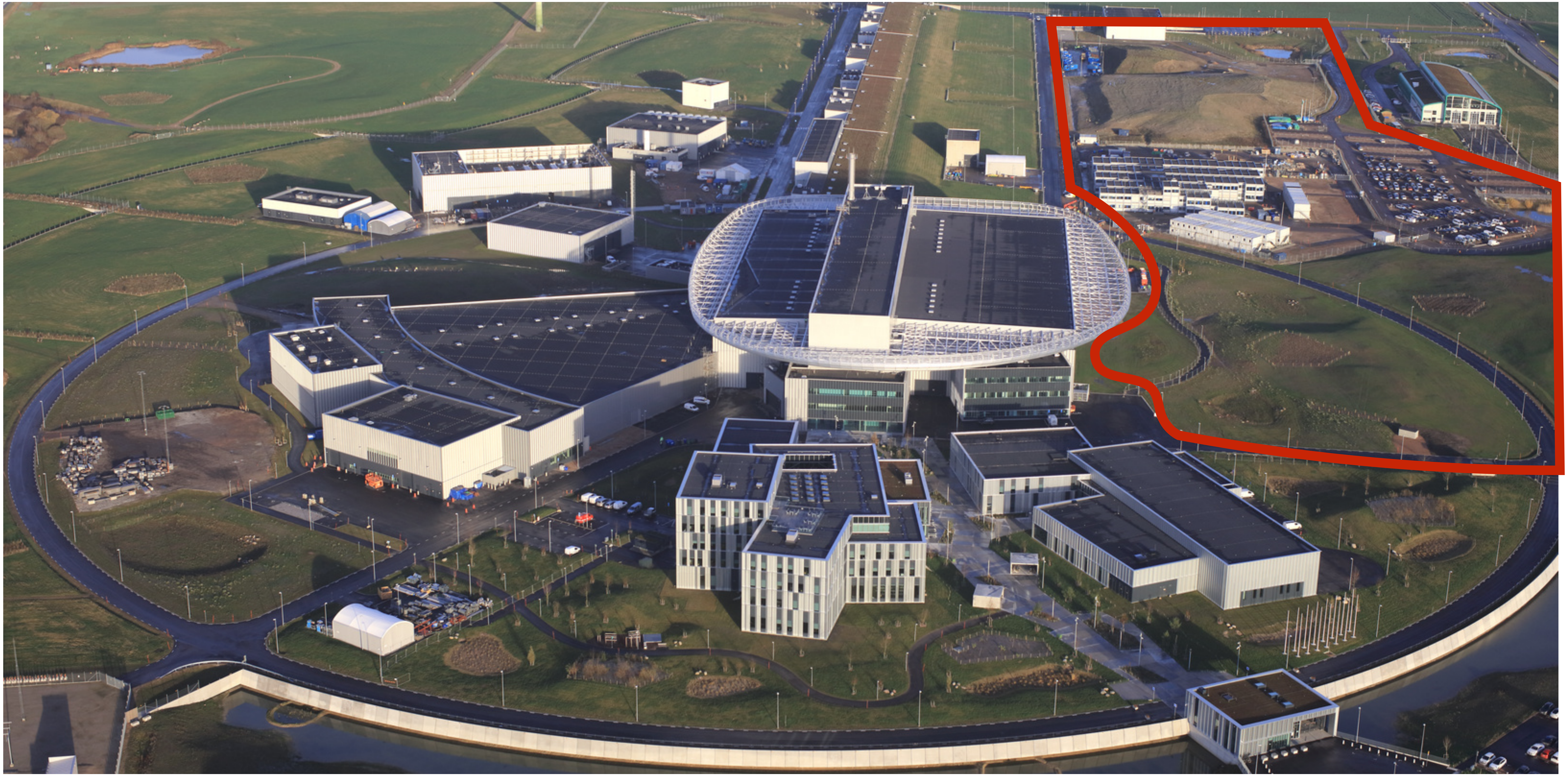




Neutrons

PSI, TUM

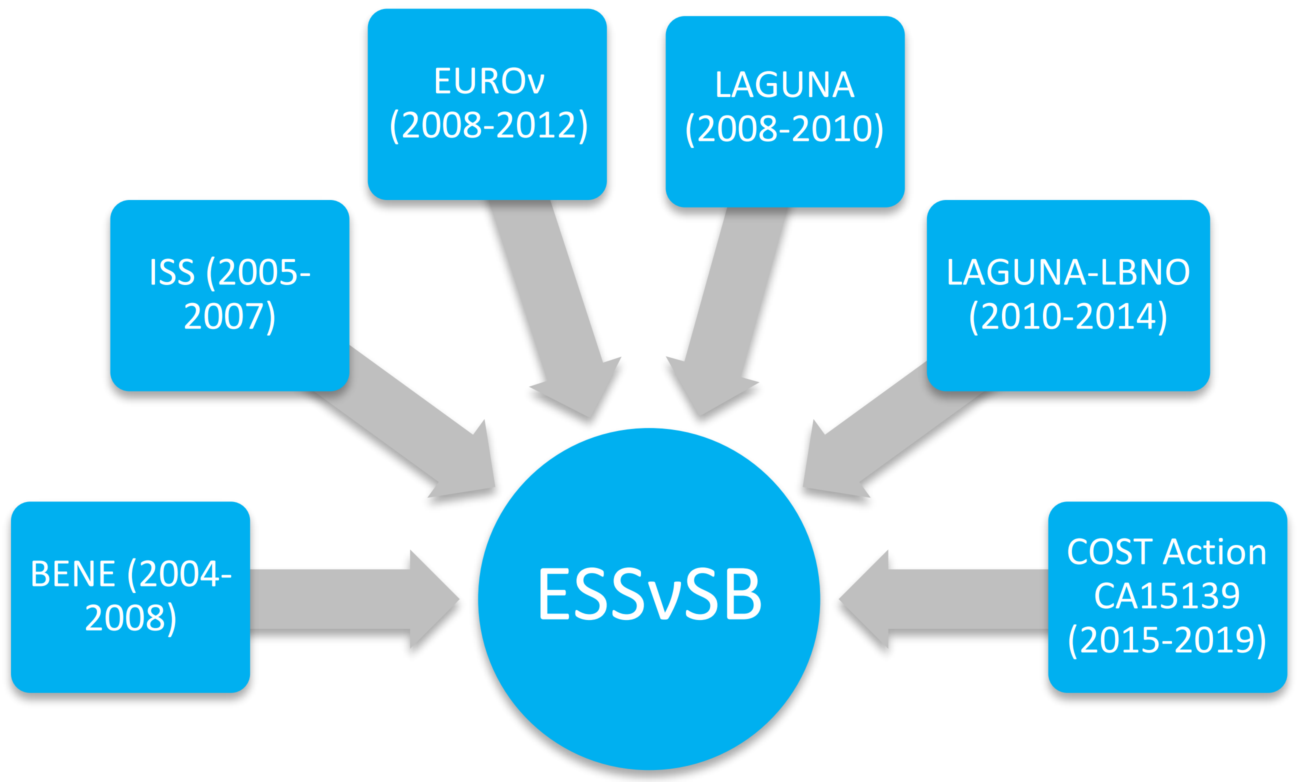
ESS

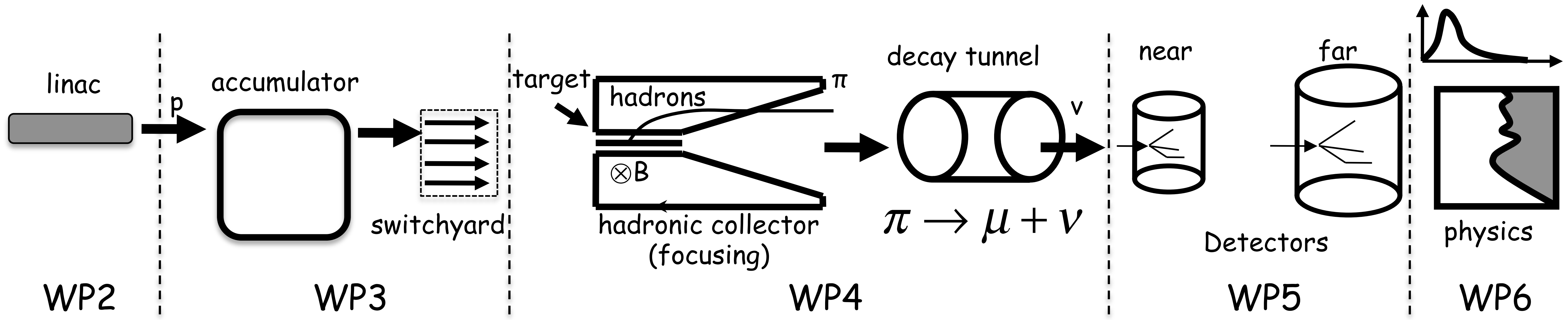


ESSnuSB

Call/Activity: A H2020 EU Design Study (Call INFRADEV-01-2017)
Title of Proposal: Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator
Proposal number: 777419
Proposal acronym: ESSnuSB
Funding scheme: RIA
Duration: 4 years
Total cost: 4.7 M€
Requested budget: 3 M€
Participants: 15 participating institutes from 11 European countries including CERN and ESS
6 Work Packages
Approved end of August 2017: 2018-2021 → Conceptual Design Report end of 2021

N.	Proposer name	Country
1	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	FR
2	UPPSALA UNIVERSITET	SE
3	KUNGLIGA TEKNISKA HOEGSKOLAN	SE
4	EUROPEAN SPALLATION SOURCE ERIC	SE
5	UNIVERSITY OF CUKUROVA	TR
6	UNIVERSIDAD AUTONOMA DE MADRID	ES
7	NATIONAL CENTER FOR SCIENTIFIC RESEARCH "DEMOKRITOS"	EL
8	ISTITUTO NAZIONALE DI FISICA NUCLEARE	IT
9	RUDER BOSKOVIC INSTITUTE	HR
10	SOFIISKI UNIVERSITET SVETI KLIMENT OHRIDSKI	BG
11	LUNDS UNIVERSITET	SE
12	AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZICA W KRAKOWIE	PL
13	EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH	CH
14	UNIVERSITE DE GENEVE	CH
15	UNIVERSITY OF DURHAM	UK
	Total:	





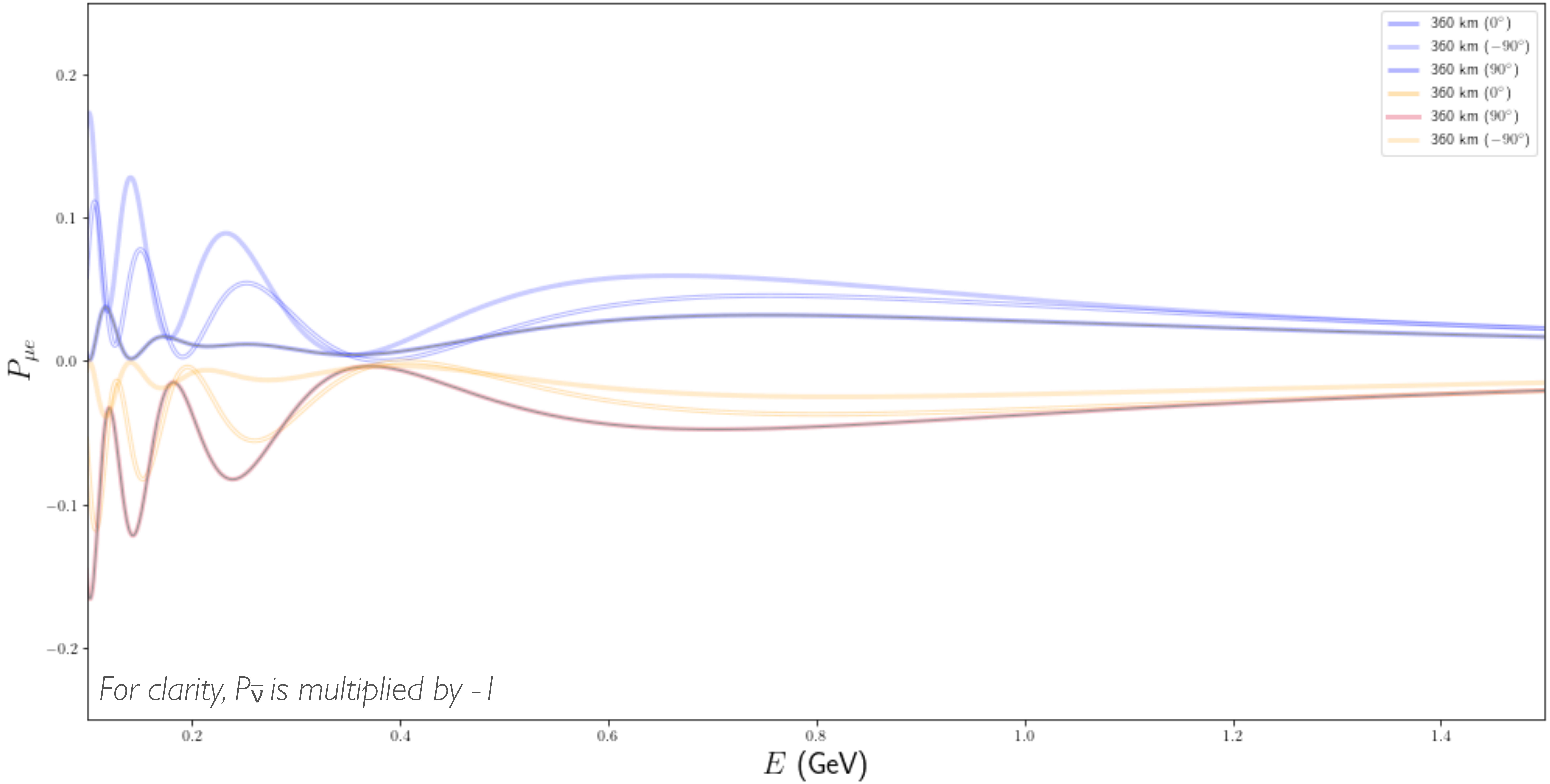
More information on: http://essnusb.eu/

Marcos Dracos

LUND TO GARPENBERG VIA ZINKGRUVAN

ESSnuSB has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 777419

Neutrino Oscillation



Stay tuned for a CERN EP seminar that will be given by by Budimir Kliček on Tuesday 12 April 2022 at 11:00 with the title 'Measuring leptonic CP violation at the second neutrino oscillation maximum with ESSnuSB'

Top Level Parameters

Design Drivers:

High average beam power	5 MW
High peak beam power	125 MW
High availability	>95 %

Key Linac parameters:

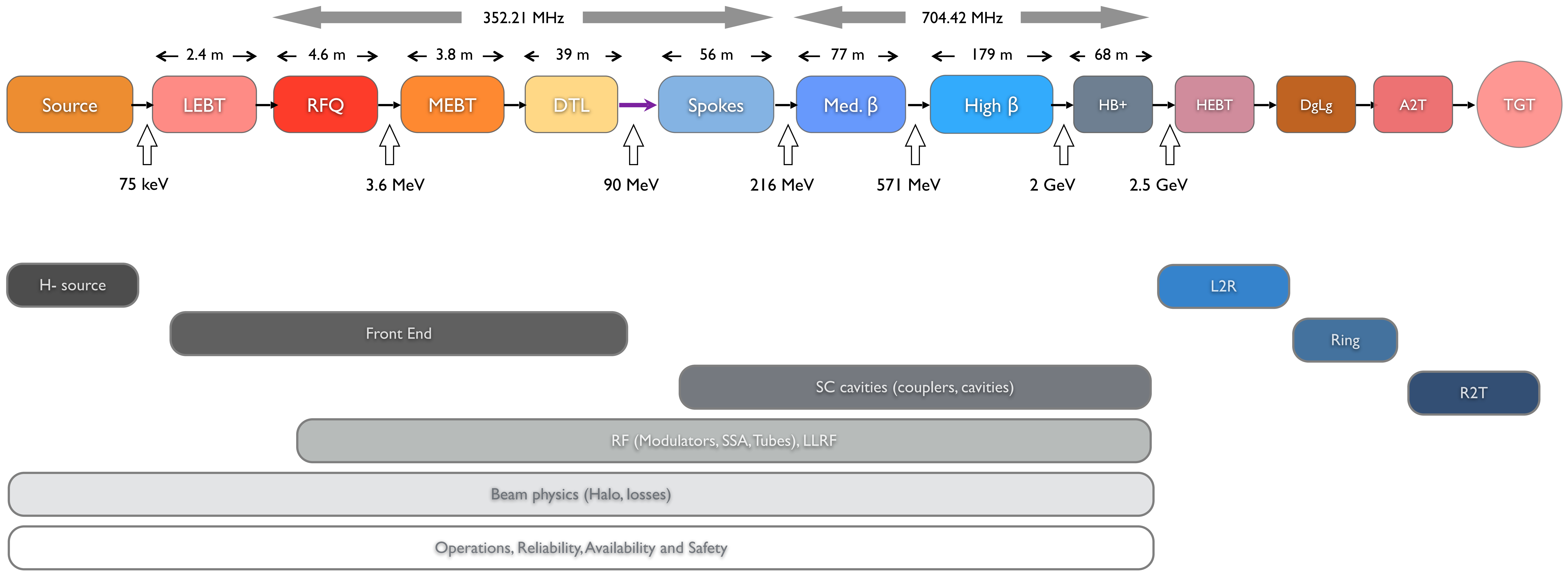
Energy	2.0 GeV
Current	62.5 mA
Repetition rate	14 Hz
Pulse length	2.86 ms
Losses	<1W/m
Ions	p

ESSnuSB beam:

Energy	2.5 GeV
Current	62 mA (50 mA)
Repetition rate	14 Hz (x 4)
Pulse length	<3.5 ms
Losses	<1W/m
Ions	H-

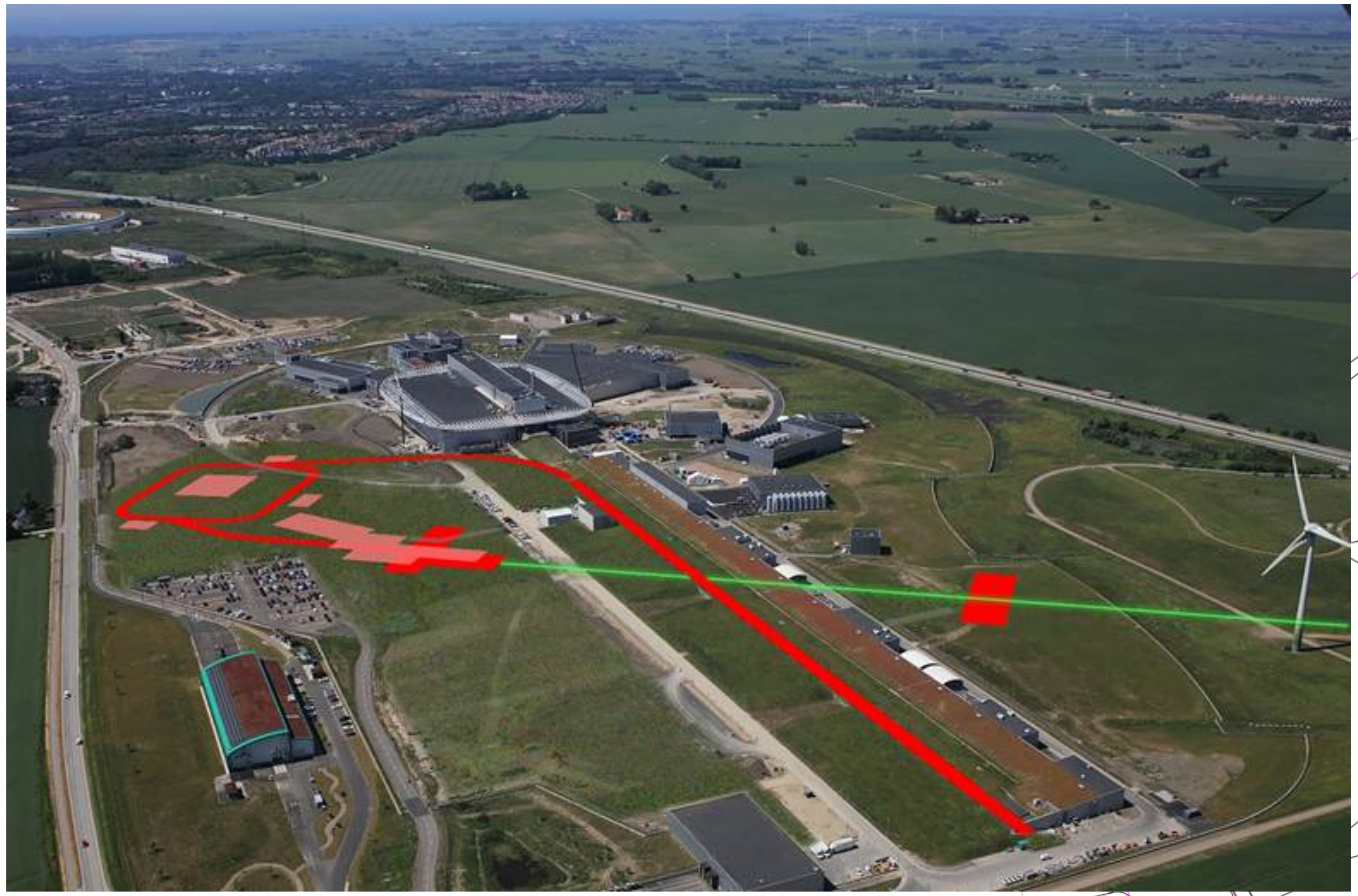
Flexible/Upgradable design

Minimize energy consumption



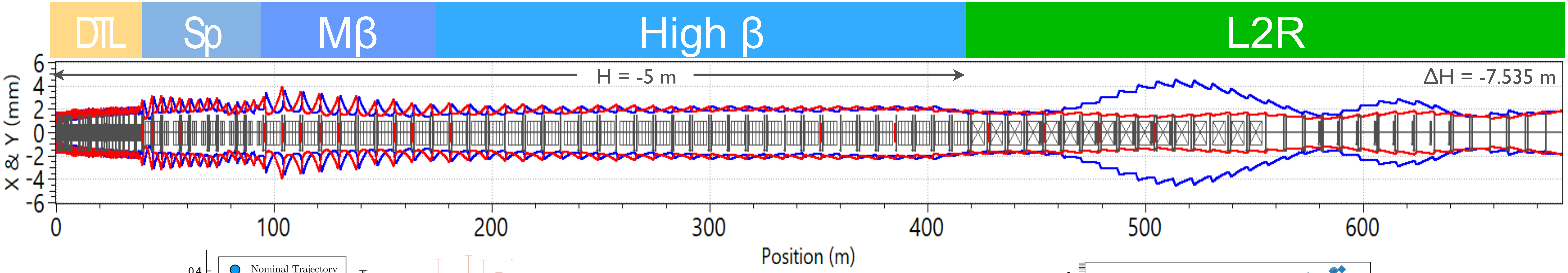
Frank Gerigk and Eric Montesinos, CERN-ADD-NOTE-2016-0050

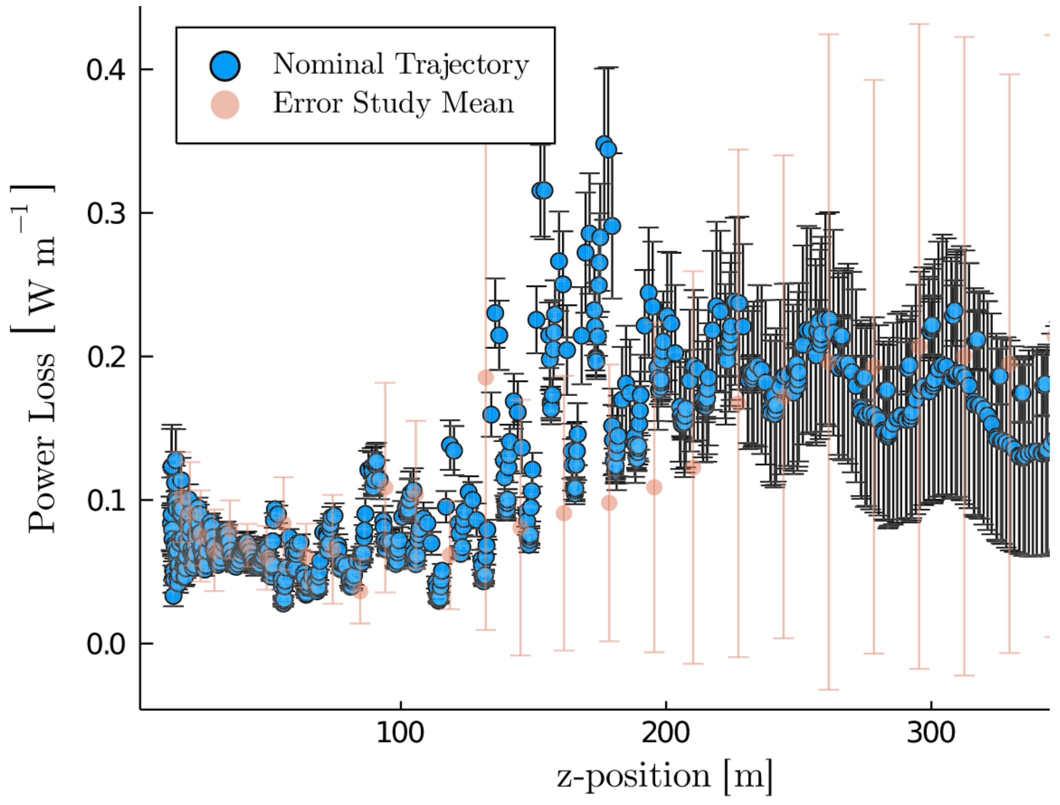
ESSnuSB Layout

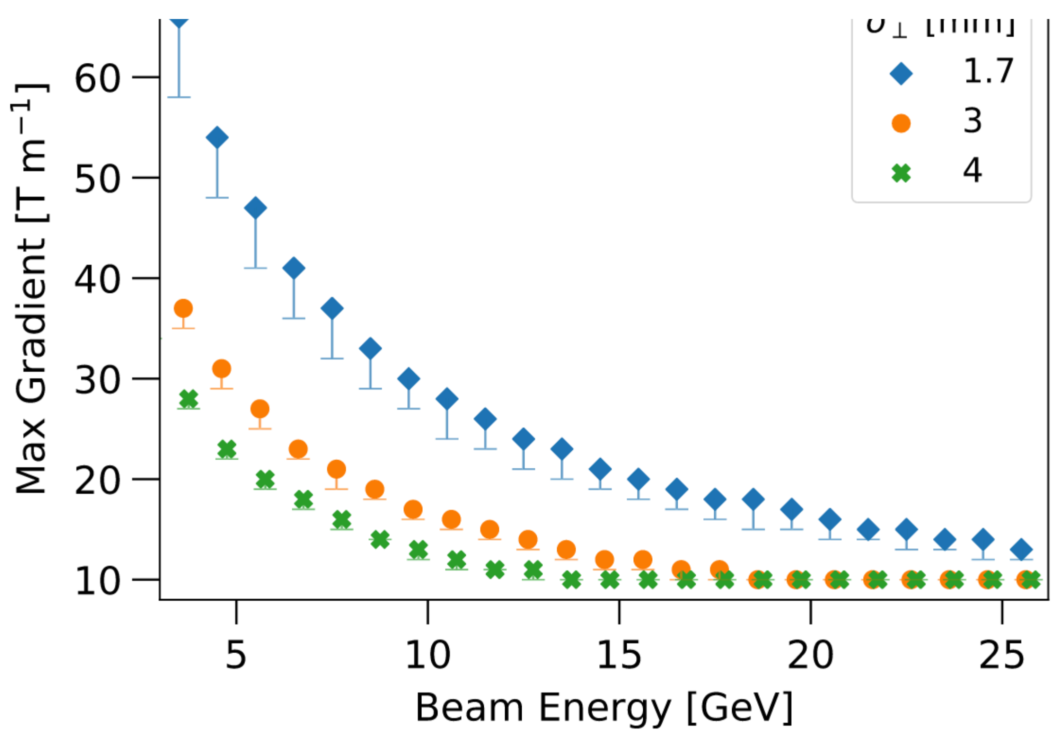


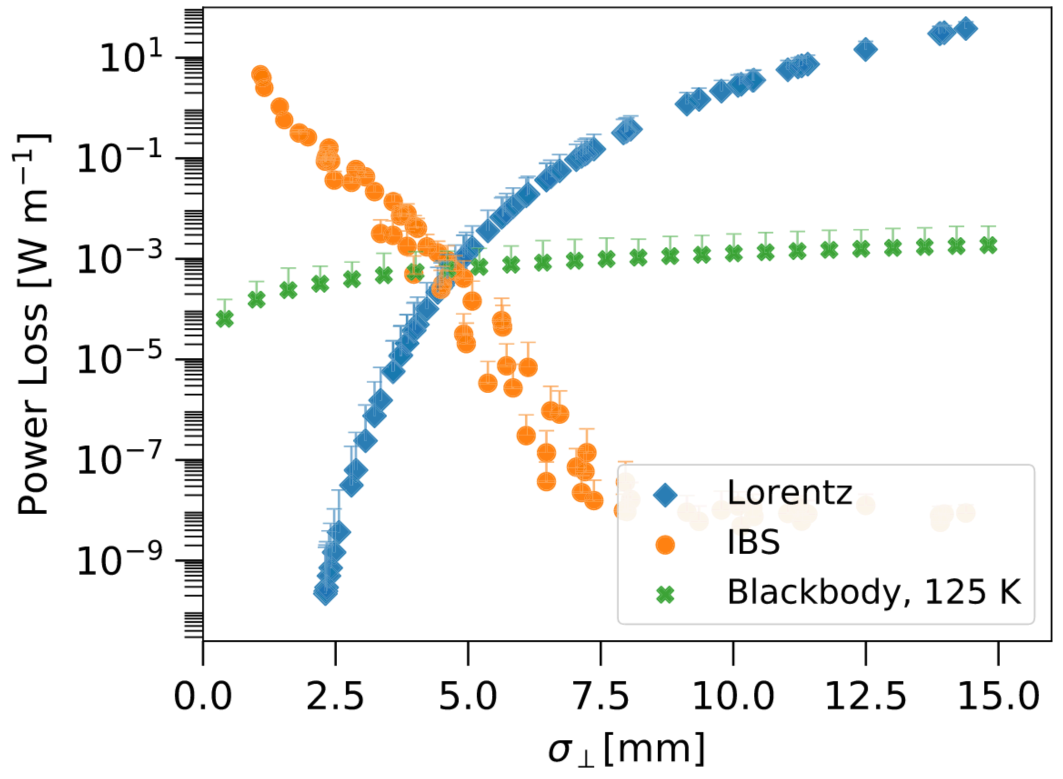
Rasmus Johansson and Nick Gazis

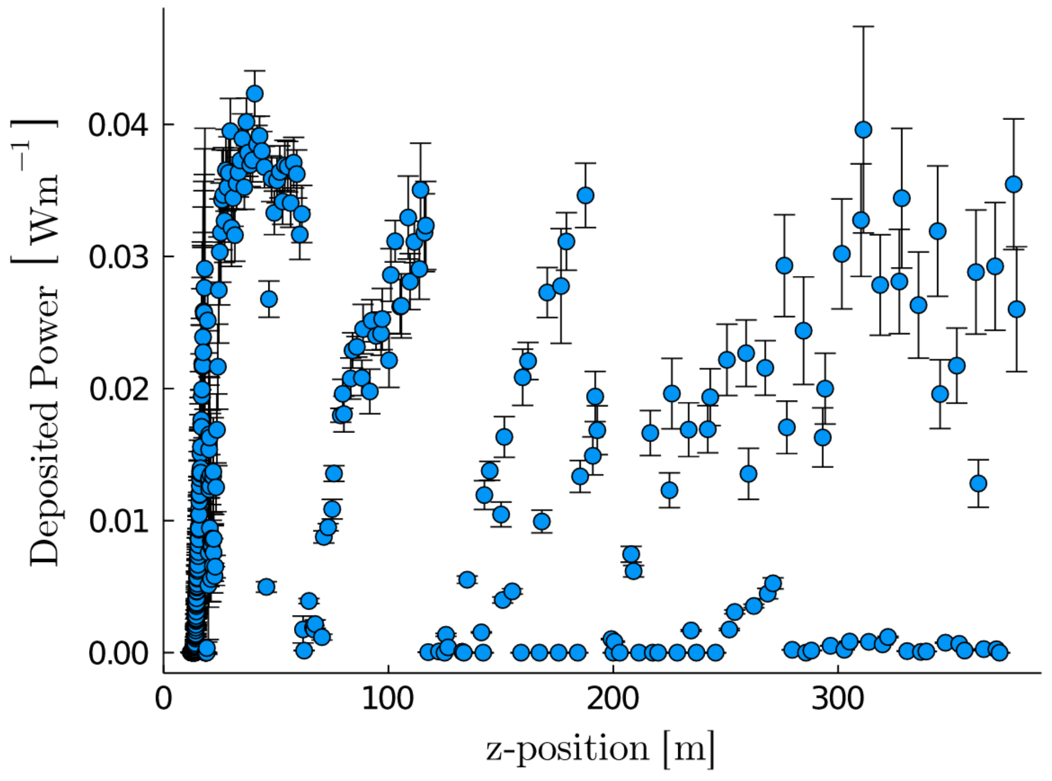
H- Transport and Losses

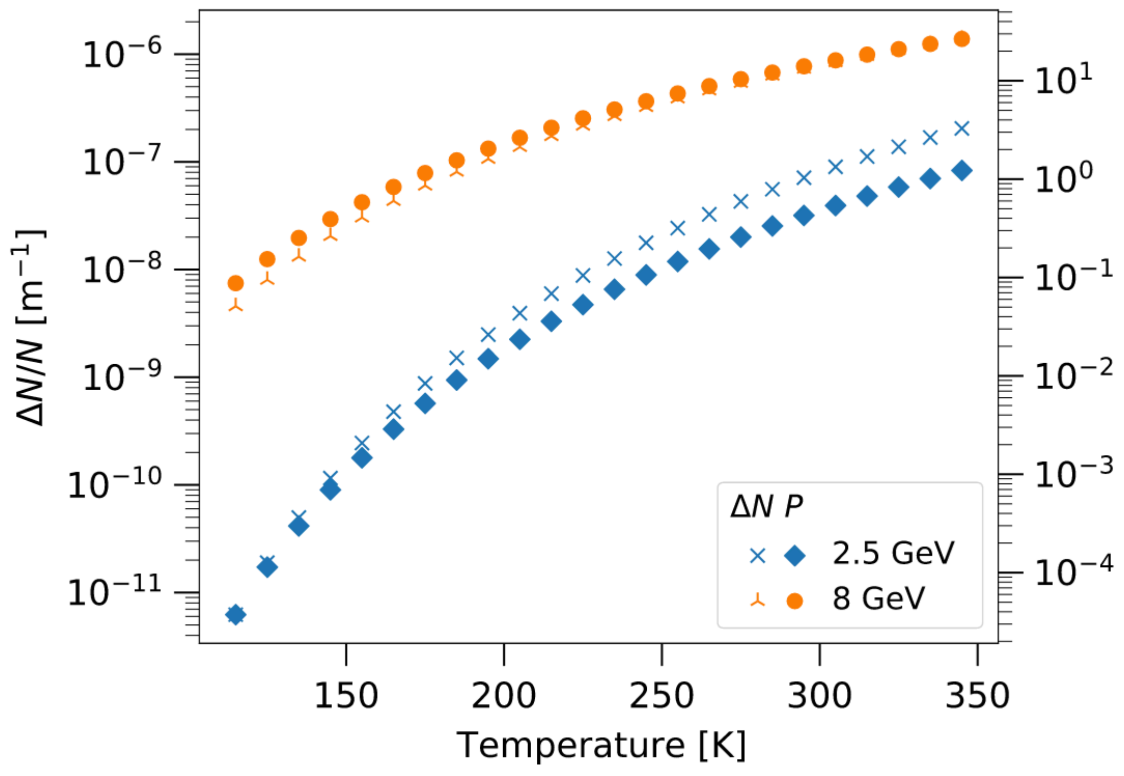


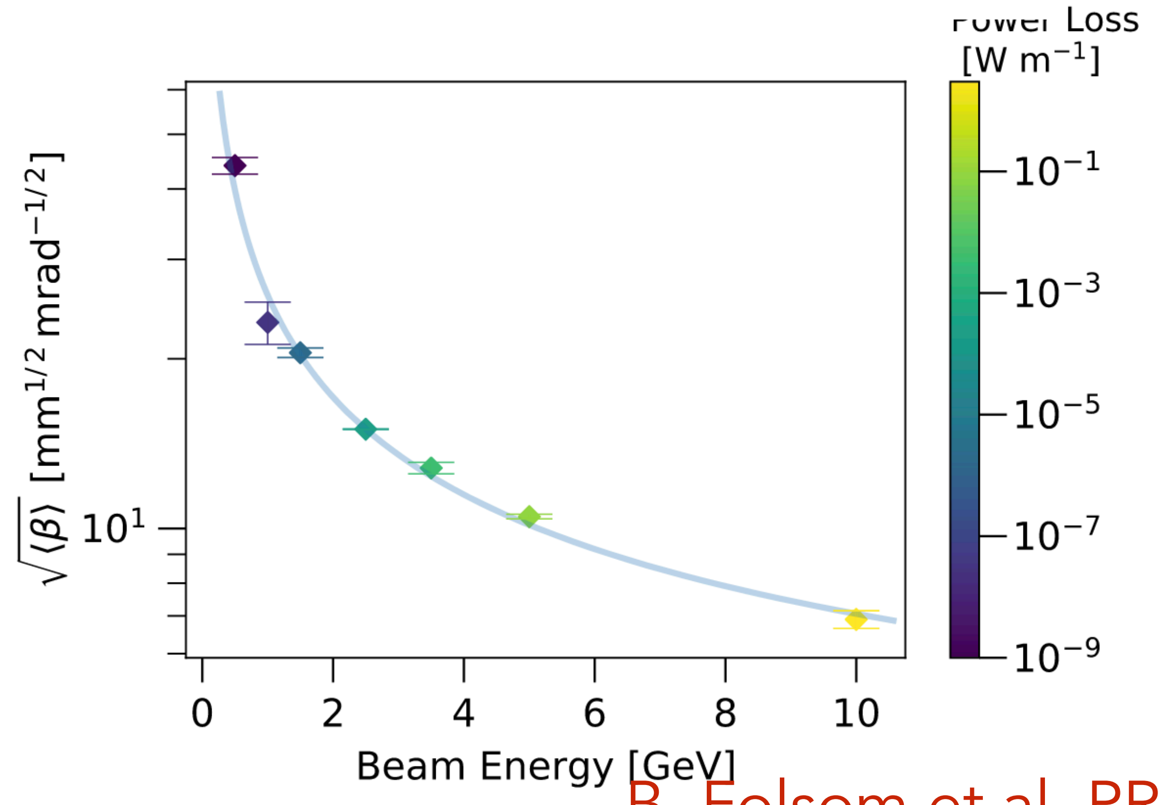






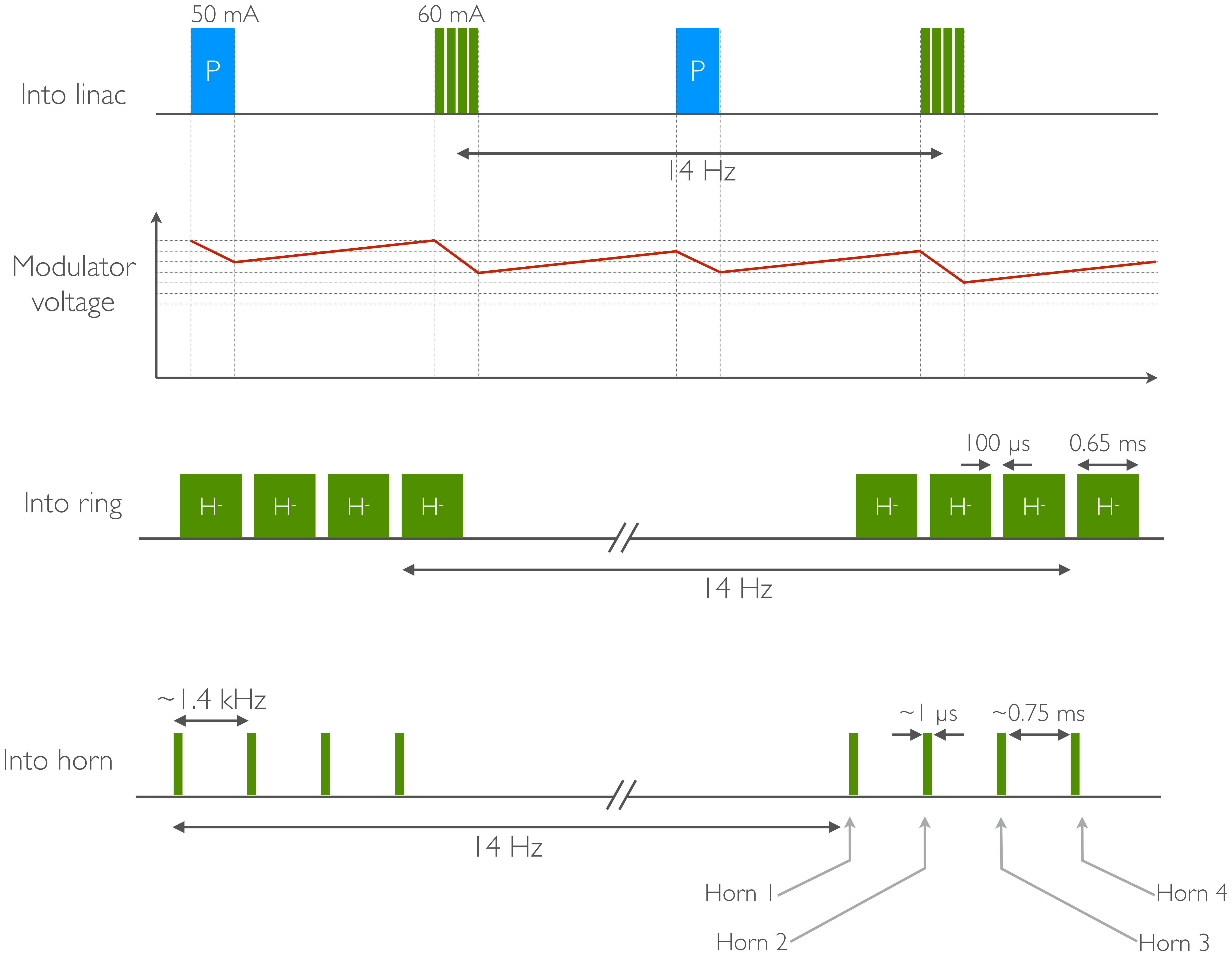




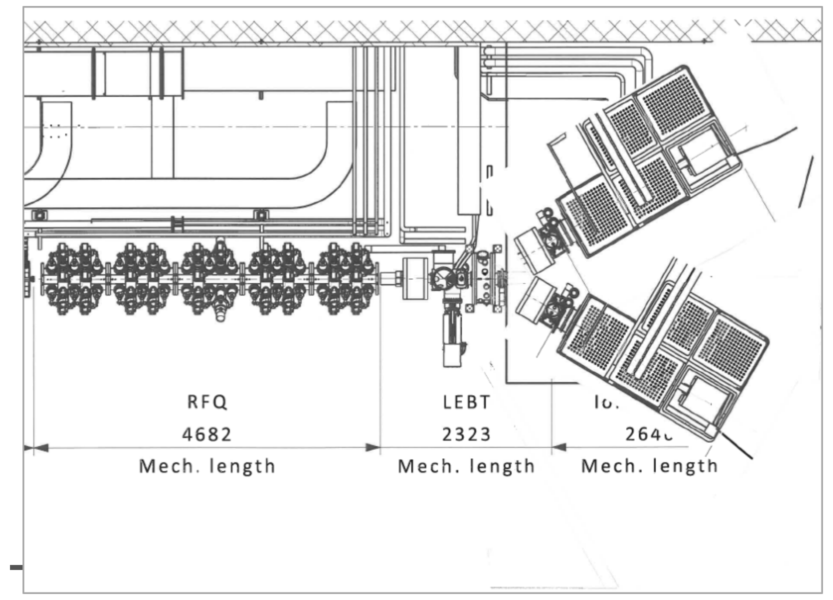


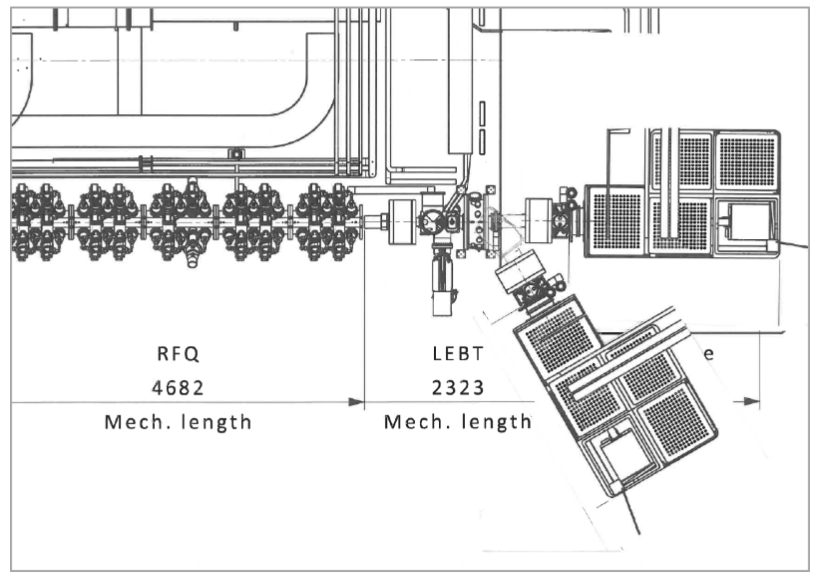
B. Folsom et al, PRAB 24, 074201 (2021)

Pulsing in the Linac, Ring and Target

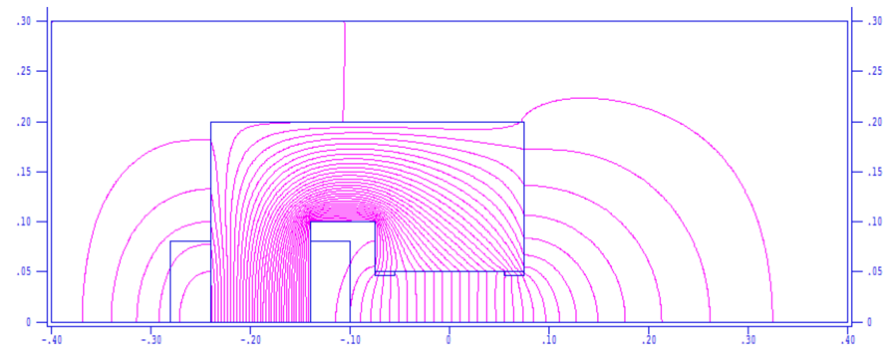


- Possibility of merging the two beams at 70 Hz





- Bending radius: 400 mm
  - pole gap: 100 mm
- A coil with100 turns
  - Inductance: 17 mH
    - possible to switch at 70 Hz
- Power supply:
  - Current: 80 A
  - Voltage: 170 V

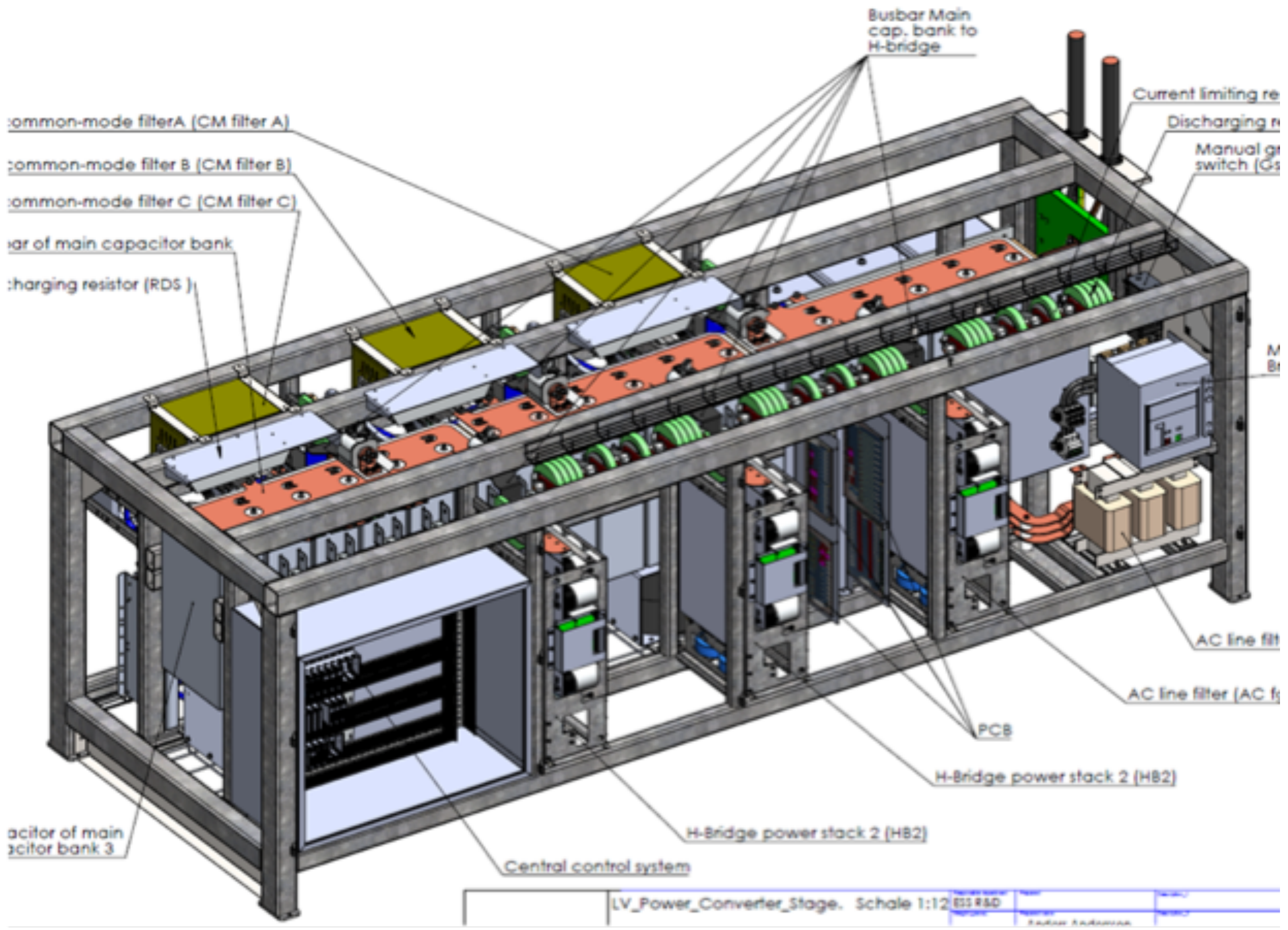


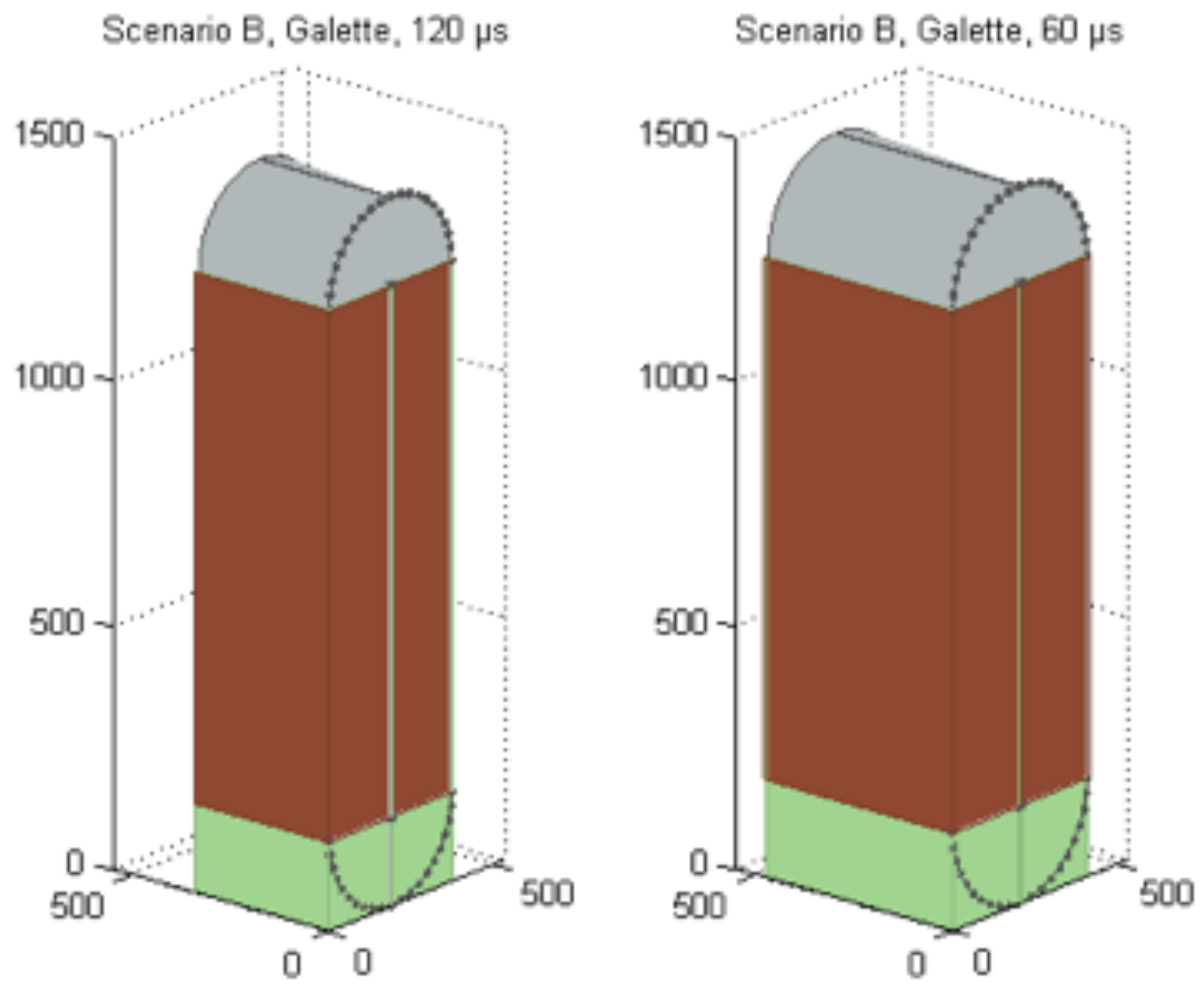
Håkan Danared, Björn Gålnander

Modulator

- Two different power upgrades for the modulators have been studied:
  - Using the SML modulators of ESS and upgrading the capacitor chargers
  - Using the SML modulators of ESS and adding pulse transformers for the H- beam

Scenario	Solution	Eta	Investment cost [M€]	Electricity cost per year [M€/y]	Increased system footprint [m²]	Total system height [m]	H^- pulse rise time [μs]
A	SML upgr.	0.82	13.4	14.6	0	3.1	< 120
B	SML upgr.	> 0.80	13.4	14.8	0	3.1	< 80
	SML + PT	> 0.80	26.3	14.8	< 2.5 x 1.5	2.4	60-120
C	SML upgr.	> 0.71	13.4	16.7	0	3.1	< 170
	SML + PT	> 0.72	26.6	16.5	< 2.5 x 1.5	2.4	50-120
Baseline	SML	0.82	N/A	7.30	N/A	2.6	N/A

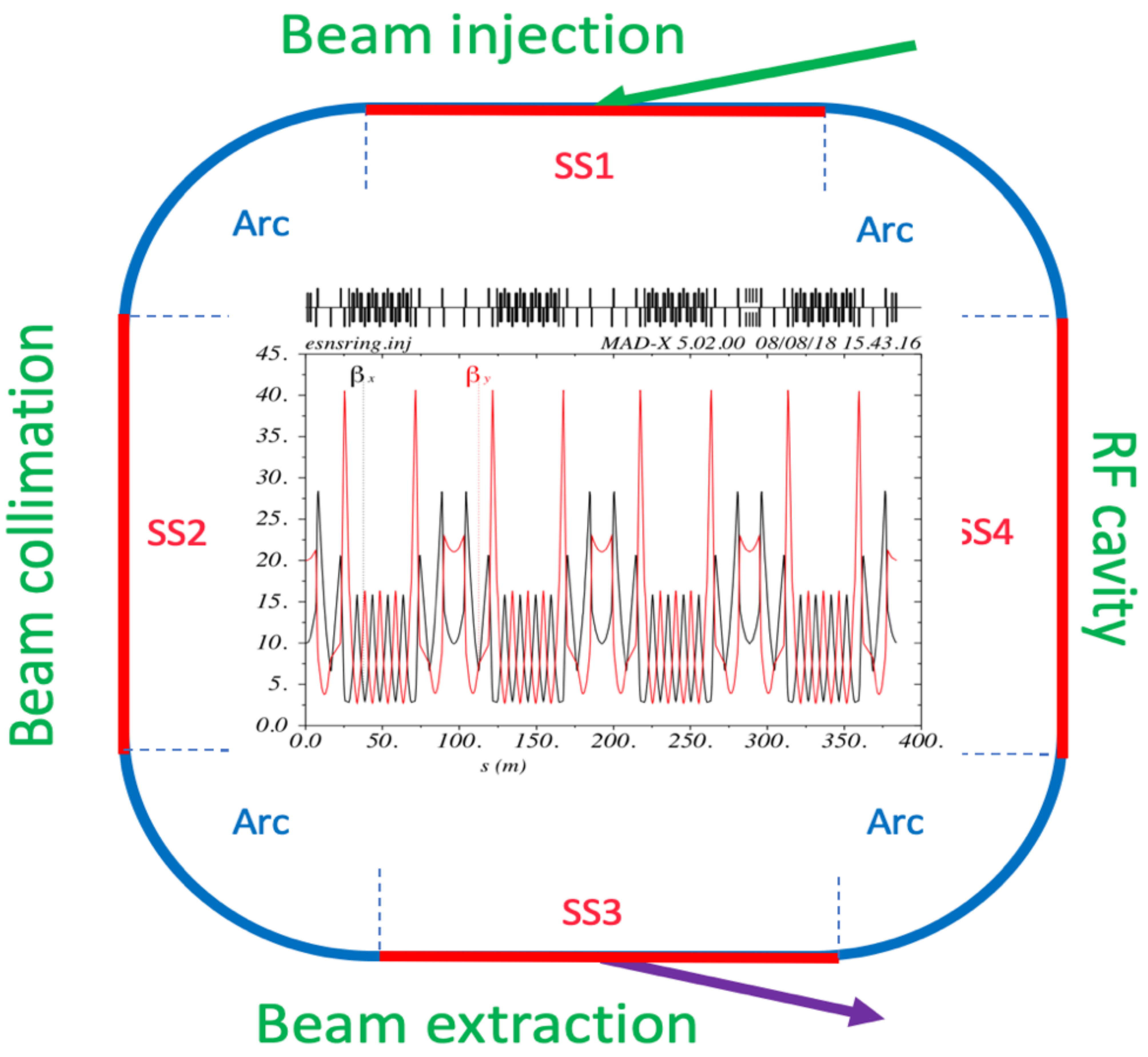




Max Collins and Carlos Martins

ACCUMULATOR DESIGN

- **Main challenges**
  - Beam loss control due to very high beam power
  - Space-charge tune shift due to very high beam intensity
  - Instabilities (e-p instability)
- **Main design requirements**
  - Ring circumference: ~ 400 m
  - Injection turns: ~ 600
  - Extraction gap: ~100 ns
  - Total beam loss (1 W/m): <10-4
  - Collimation efficiency: >90%
  - Space-charge tune shift: <0.1
- **Lattice design**
  - Developed by Horst Schönauer at CERN
  - Circumference: 384 m
  - 4-fold symmetry
  - 4 straight sections (SS1~SS4) and 4 arc sections (Arc)
  - Fixed injection chicane and fast programmable bump for injection painting

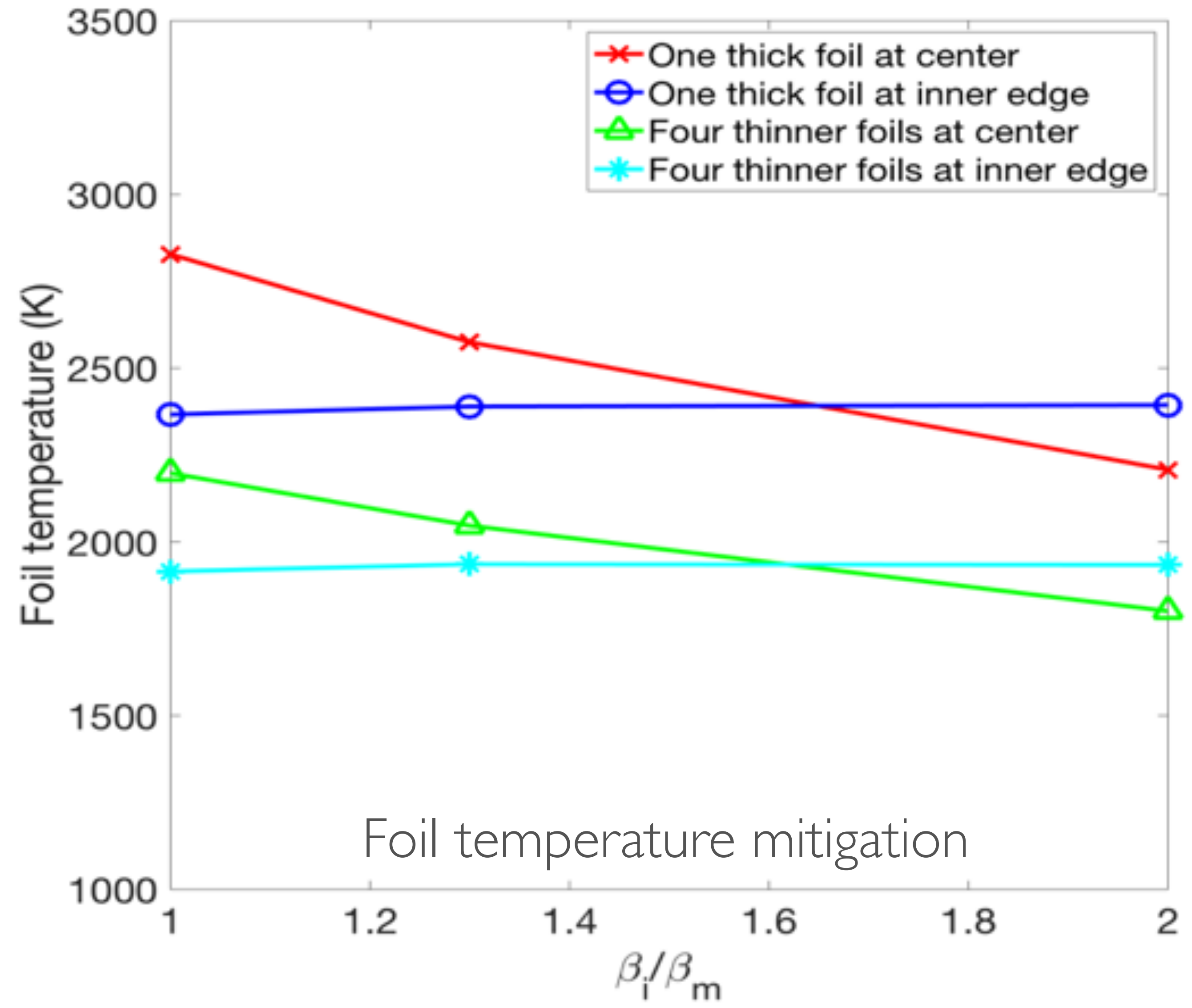


	ESSnuSB	PSB	SNS	J-PARC RCS
Ring circumference	384 m	157 m	248 m	348 m
Beam energy at injection	2.5 GeV	160 MeV	1.0 GeV	400 MeV
Beam energy at extraction	2.5 GeV	2.0 MeV	1.0 GeV	3.0 GeV
Number of injected particles	2.3e14	1.6E13	1.5E14	8.3E13

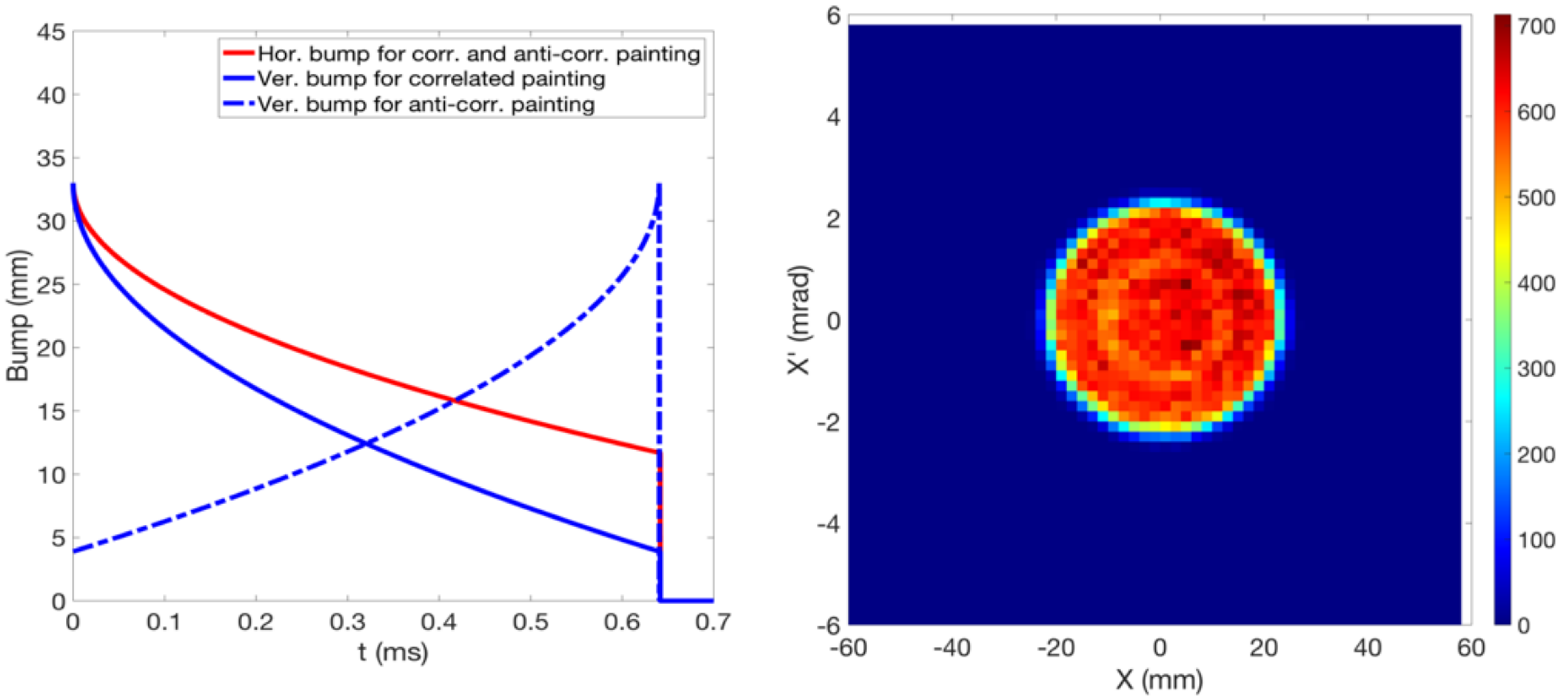
Maja Olvegård, Ye Zou

Beam Injection

- **Foil stripping and laser stripping**
  - Foil stripping: widely used in proton synchrotrons or accumulators, very challenging due to high power
  - Laser stripping: a promising alternative method
- **Painting**
  - Mitigate space charge issue
  - Mitigate foil temperature issue
- **Foil temperature issue mitigation**
  - Mismatch injection
  - Splitting the foil along beam direction
  - Moving injection point



Foil temperature mitigation



Painting optimization

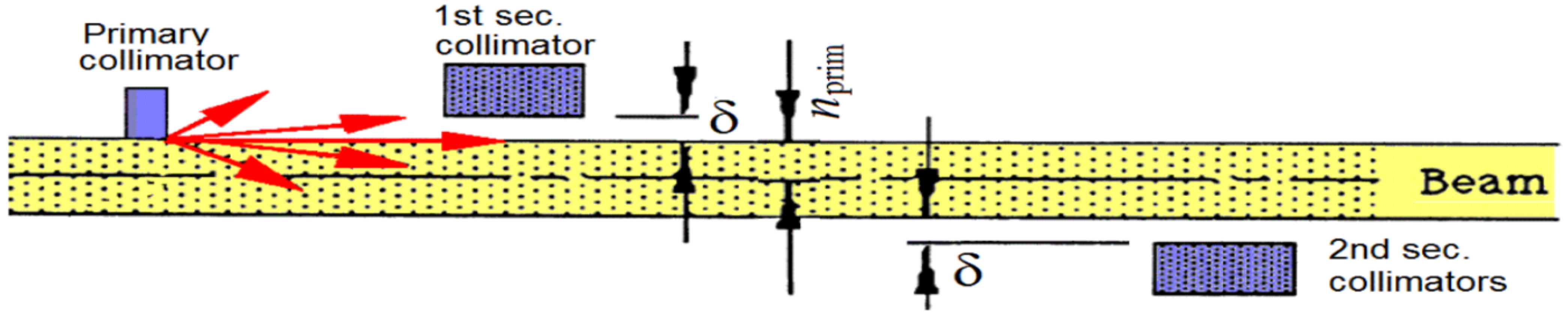
- Painting to quasi-uniform beam, with 100% emittance of 60 π mm mrad in both planes
- Very small tune spread (~0.05)
- Foil temperature under 2000 K

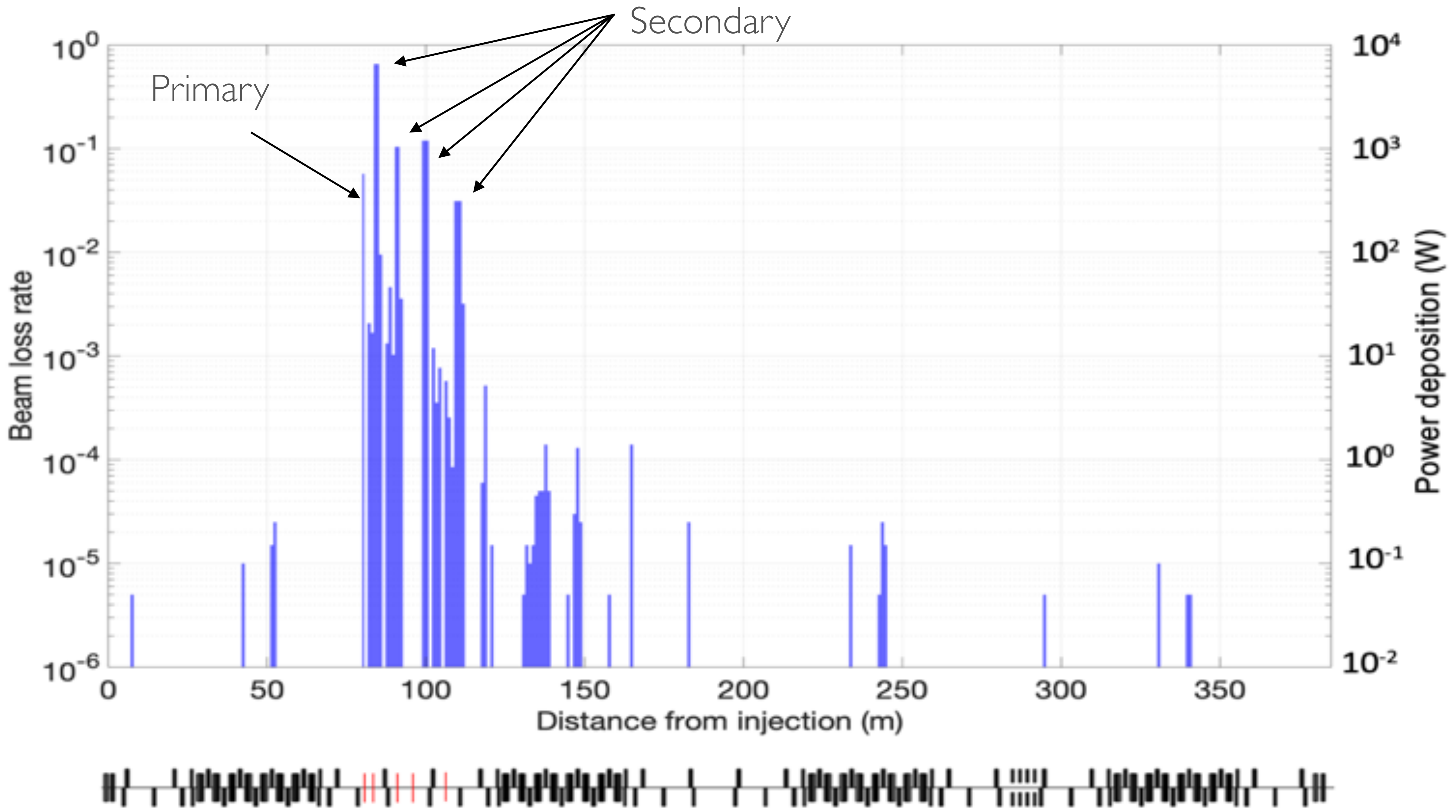
Ye Zou

Beam Collimation

- **Two-stage collimation system:**
  - A thin primary collimator to scatter beam halo particles
  - followed by a set of secondary collimators at optimal locations to absorb the scattered particles
- **Materials:**
  - Primary: Tantalum
  - Secondary: Tungsten or Copper
- **Thickness/length:**
  - Primary: 6 mm
  - Secondary: 1.5 m
- **Collimator acceptance:**
  - Primary/Secondary: 70/120 π mm mrad
- Optimal phase advances between primary and secondary collimators to maximize interception efficiency
- Numerical simulations to evaluate the performance of the collimation system

Two-stage collimation system with 97% efficiency



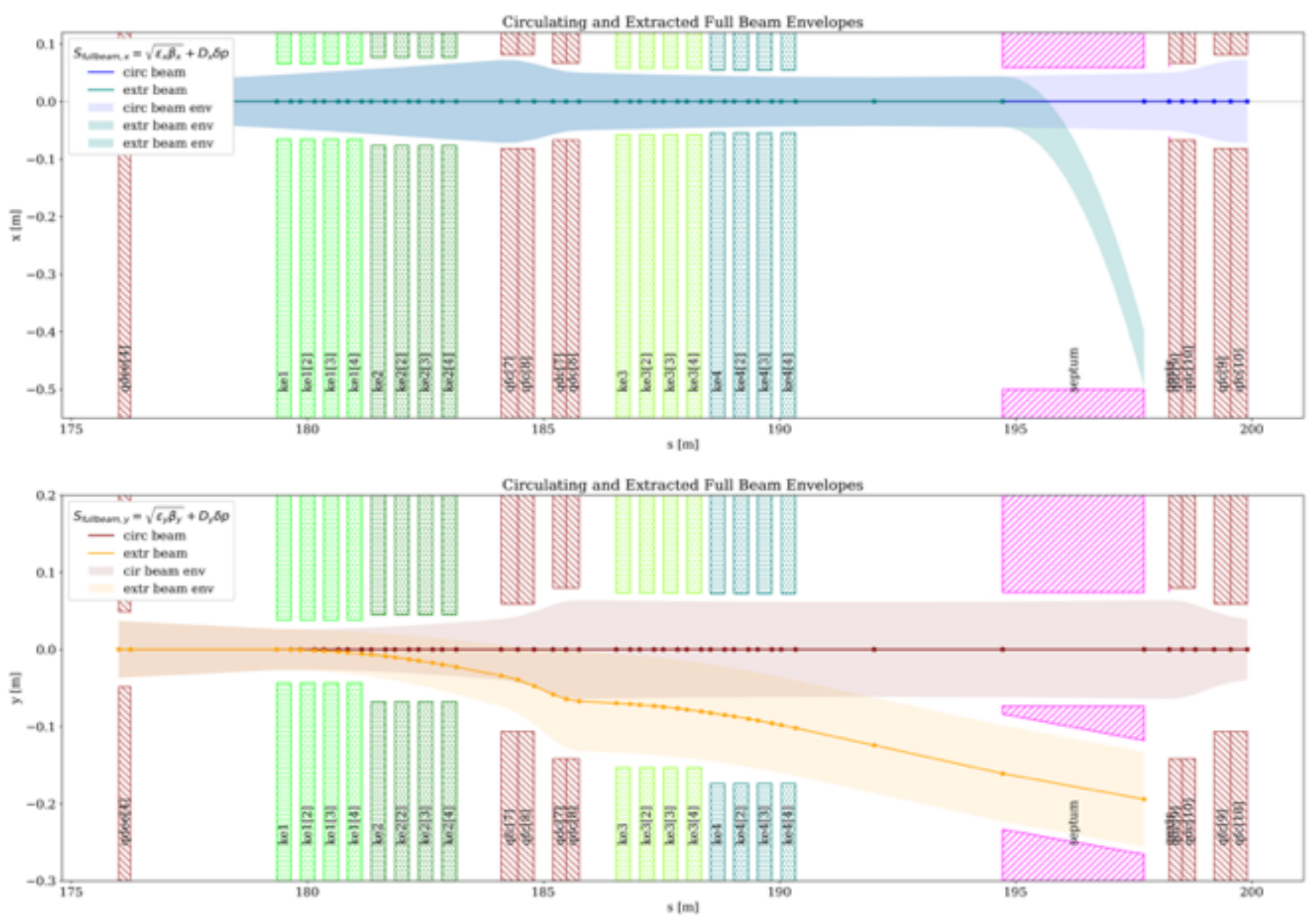


Beam loss map

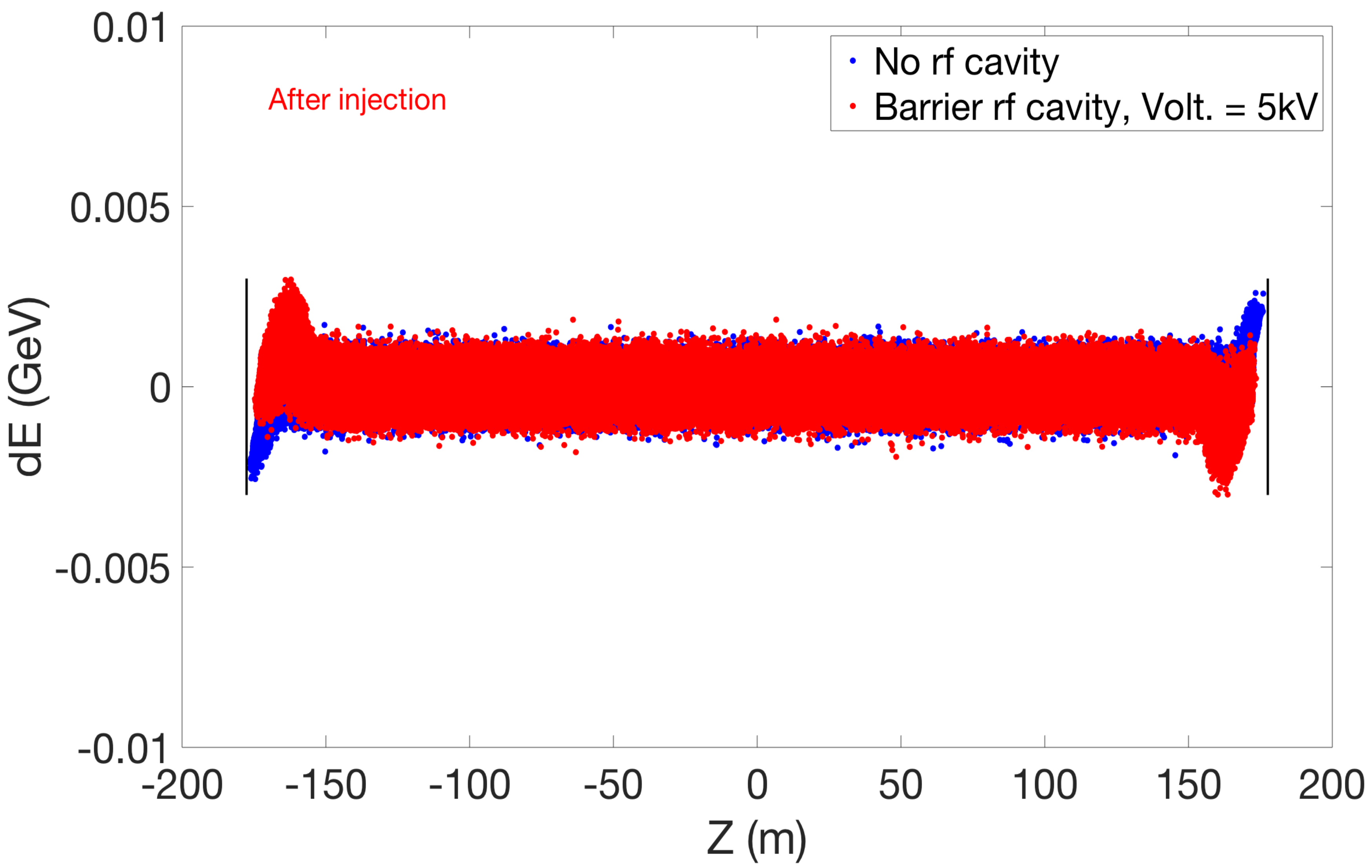
Ye Zou

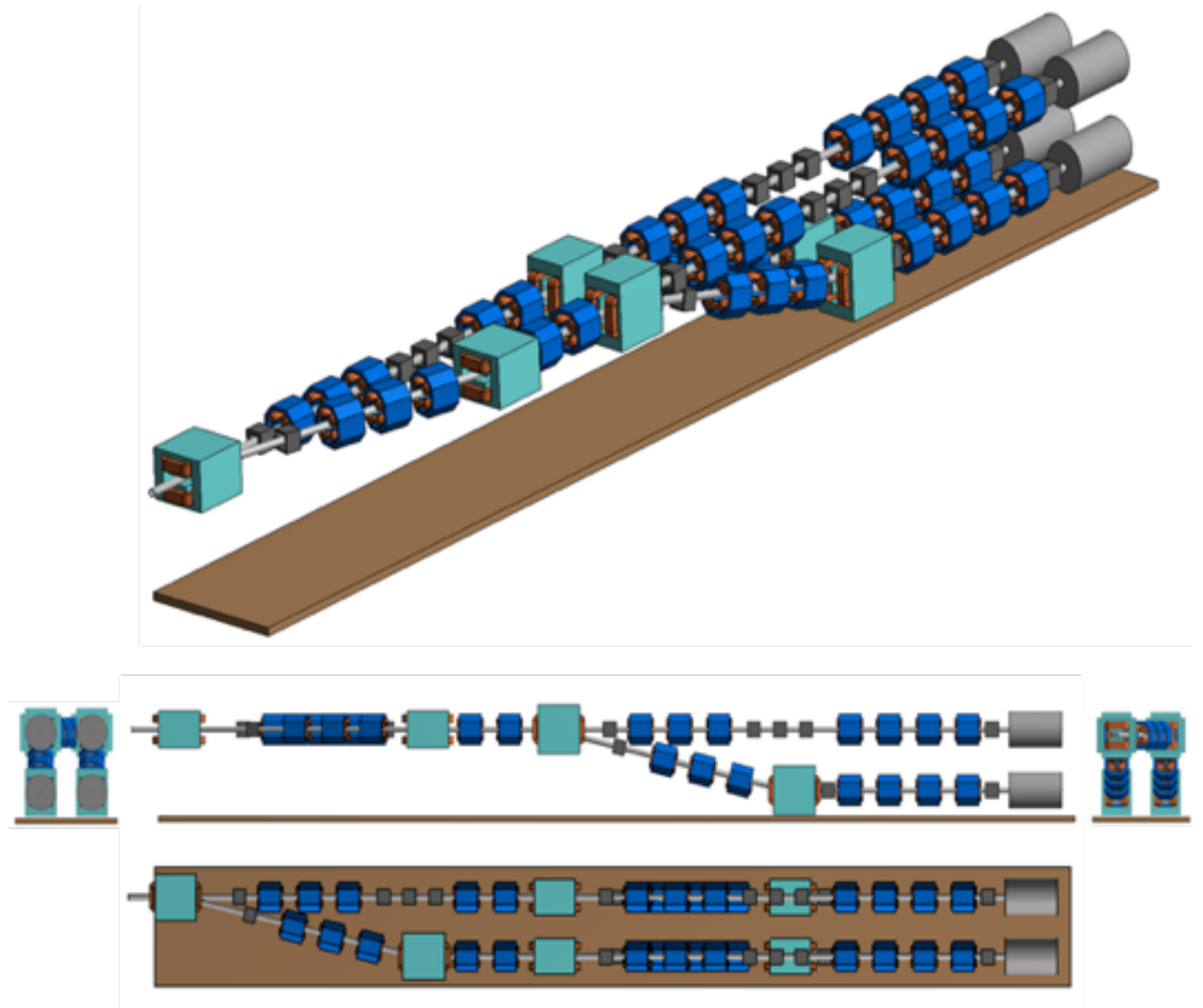
Beam Extraction, RF and Switchyard

- **Beam extraction**
  - Single-turn extraction system is designed to extract the full beam in a single turn after accumulation
  - Fast magnets (kickers) to extract the beam vertically out of the ring during the extraction gap of 100-130 ns
  - Horizontal deflector (septum) to deflect the beam by 16.8 deg to the start of the extraction line
- **Challenges**
  - Loss-free extraction ⇒ optimize aperture sizes
  - Rise-time of kickers ⇒ aperture size, B-field, technology
- **RF cavity**
  - RF cavity to keep the extraction gap clean while keep energy spread small
  - Barrier bucket is chosen due to its very small leakage risk and small energy spread (±0.15%)
  - Aperture optimized to make rise-time requirement easier to reach
- **Switchyard**
  - Switch and direct the beam pulses to the 4 horns



The circulating and extracted beam trajectories and beam envelops (100% acceptance)





Androula Alekou, I. Efthymiopoulos, Y. Zou, E. Bouquerel

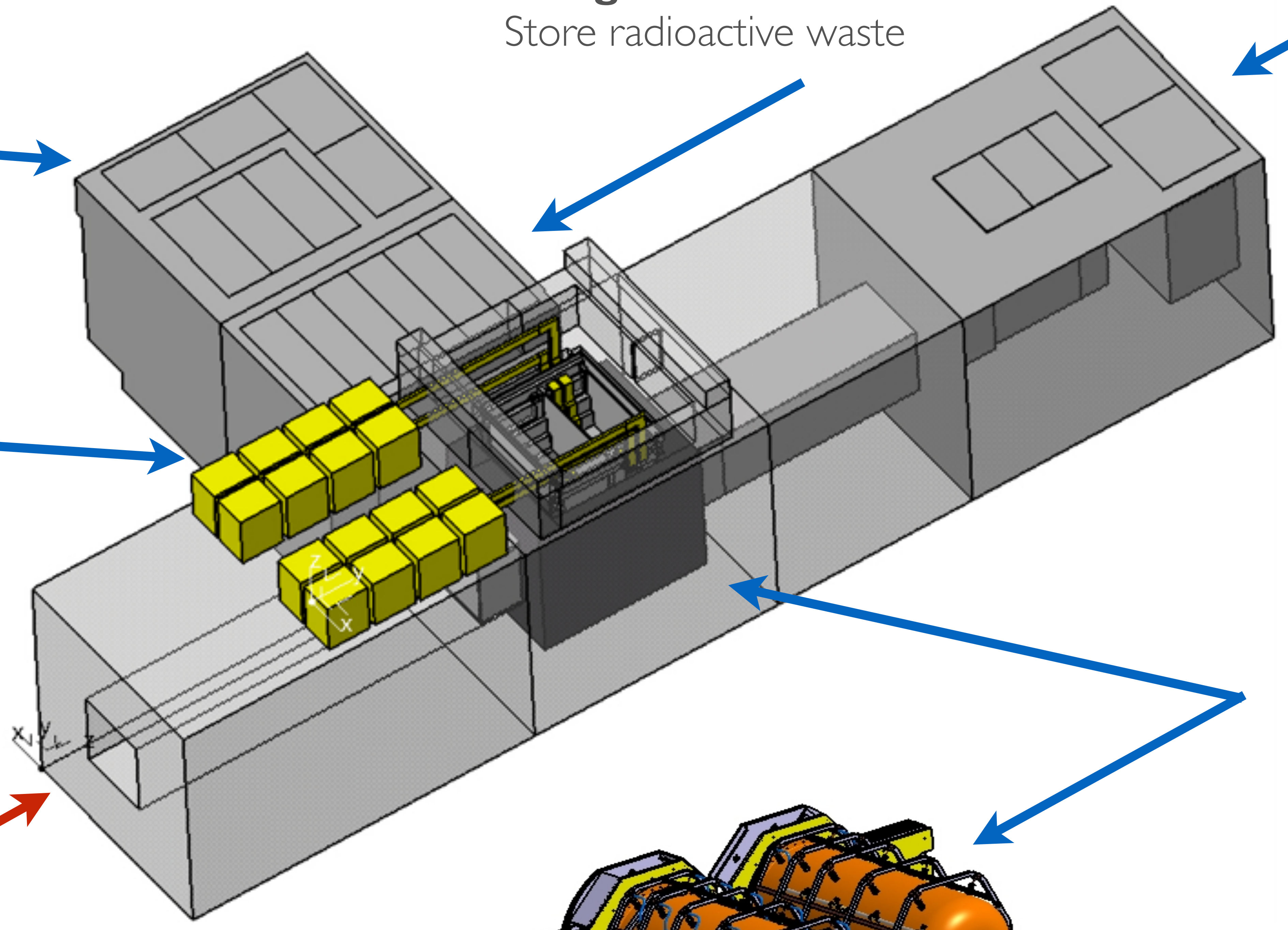
TARGET STATION DESIGN

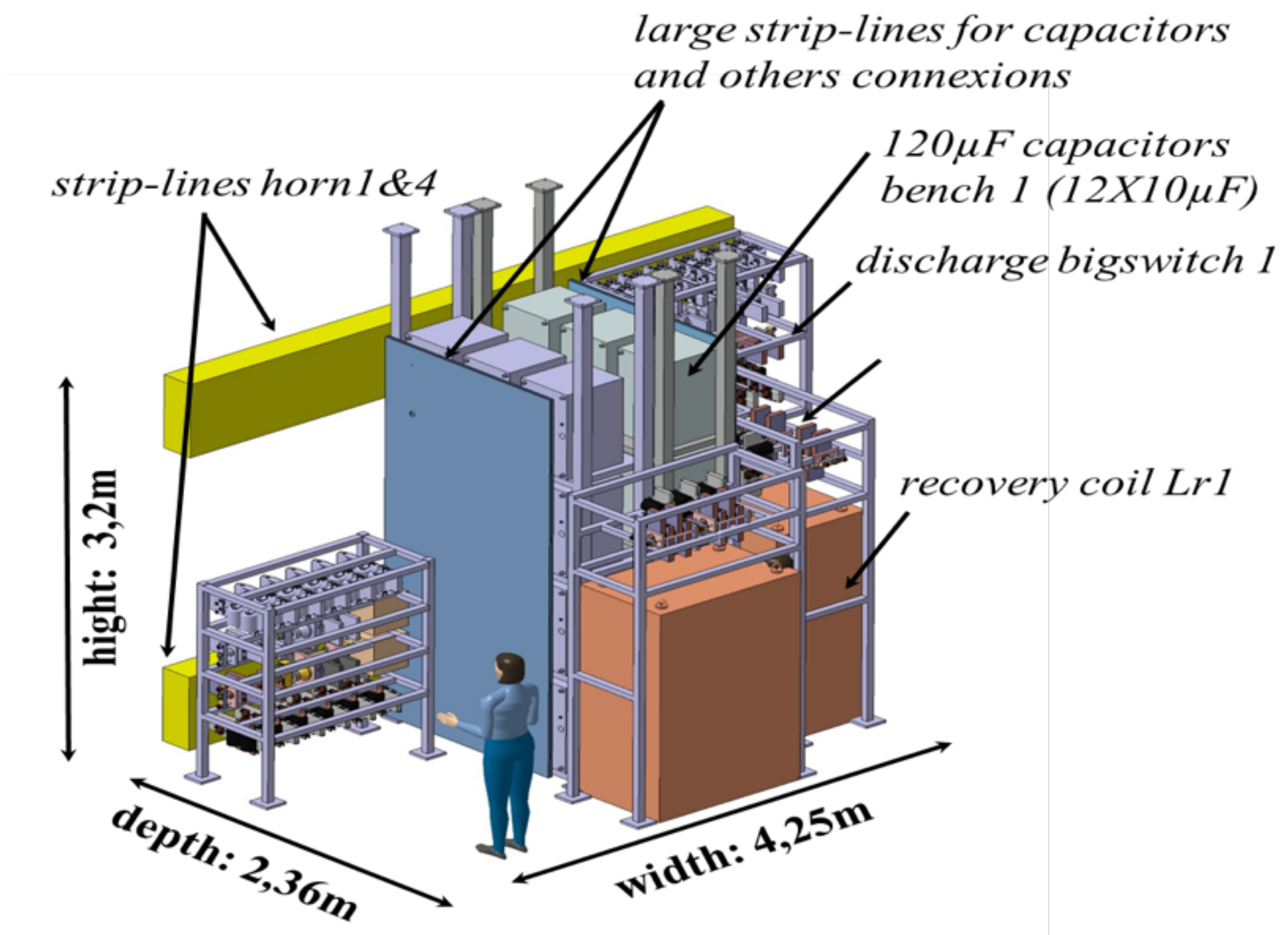
Hot Cell
Able to manipulate/repair
Hadron collector.
Work under radioactive environment.

Morgue
Store radioactive waste

Beam Dump
At the end of Decay tunnel 25 m (baseline)

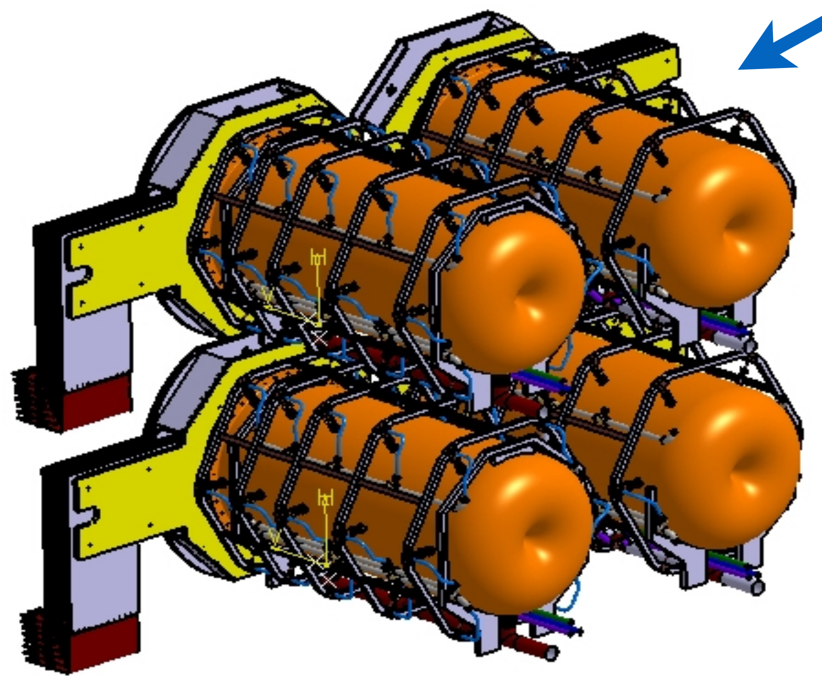
Power Supply Unit
- 16 modules (350 kA pulse/14 Hz)
- Located above the beam switchyard
- Outside of the radioactive part of the facility
- Good position to synchronize with switchyard PSU





Proton Beam
4 x 1.25 MW

Hadronic Collector
Four Horn System



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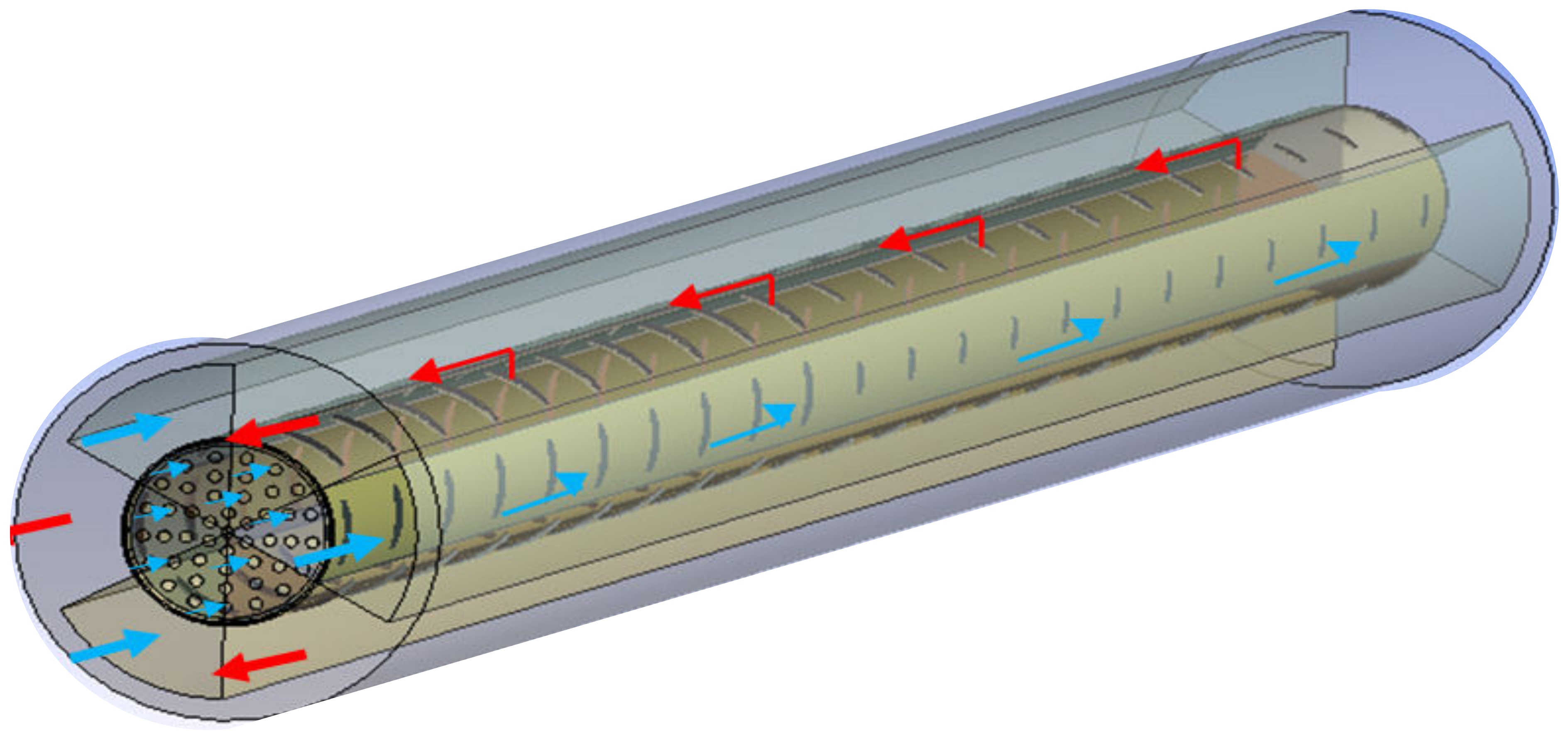
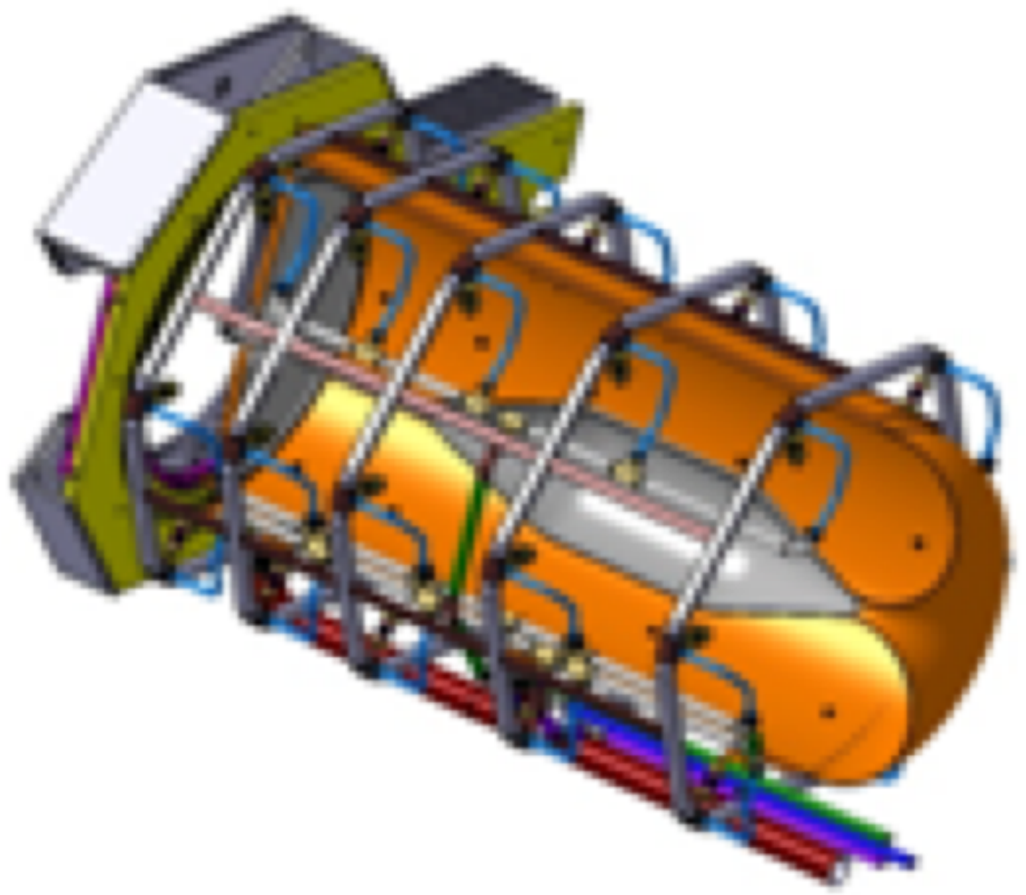
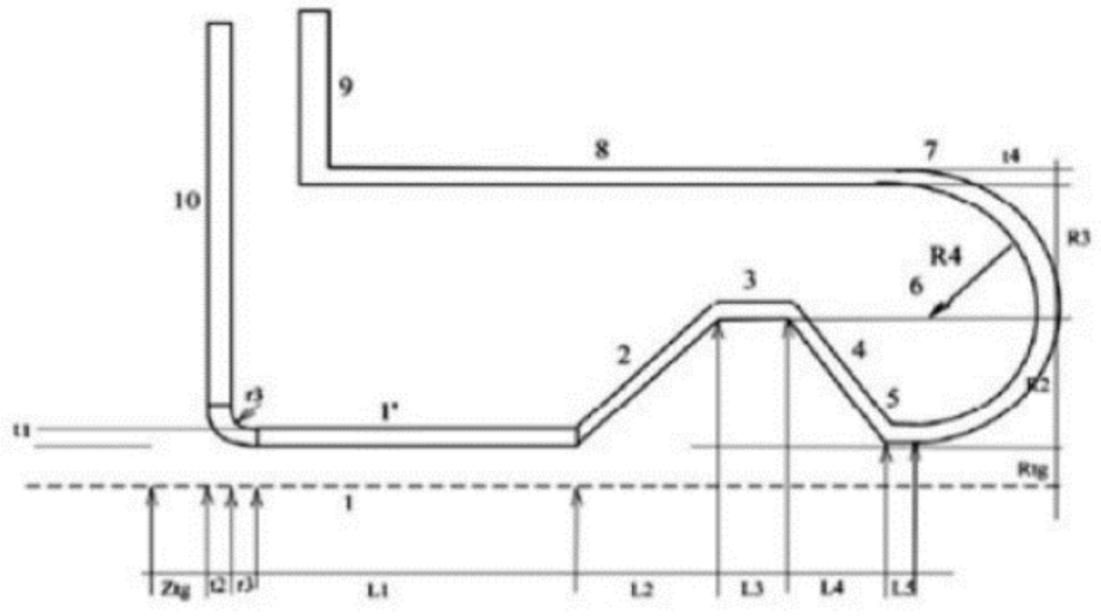
HADRONIC COLLECTOR

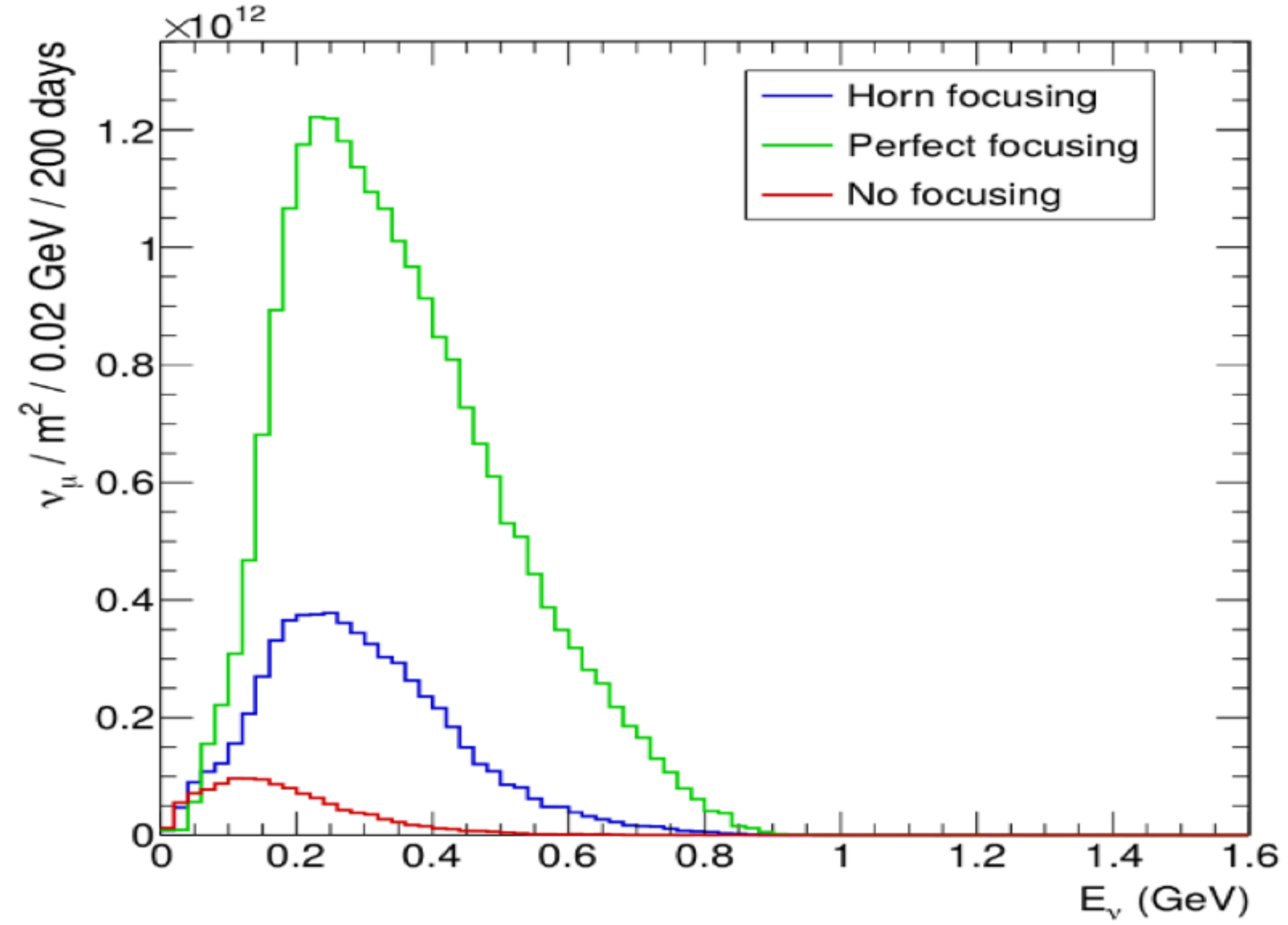
- **Packed Bed Target**
  - Power 1.25 – 1.6 MW
  - Potential heat removal rates at the hundreds of kW level
  - Helium cooling (10 bars)
  - Separated from the horn
- **Focusing System**
  - 4-horn+4 target system to accommodate the MW power scale
  - Packed bed target integrated into the inner conductor : very good physics results





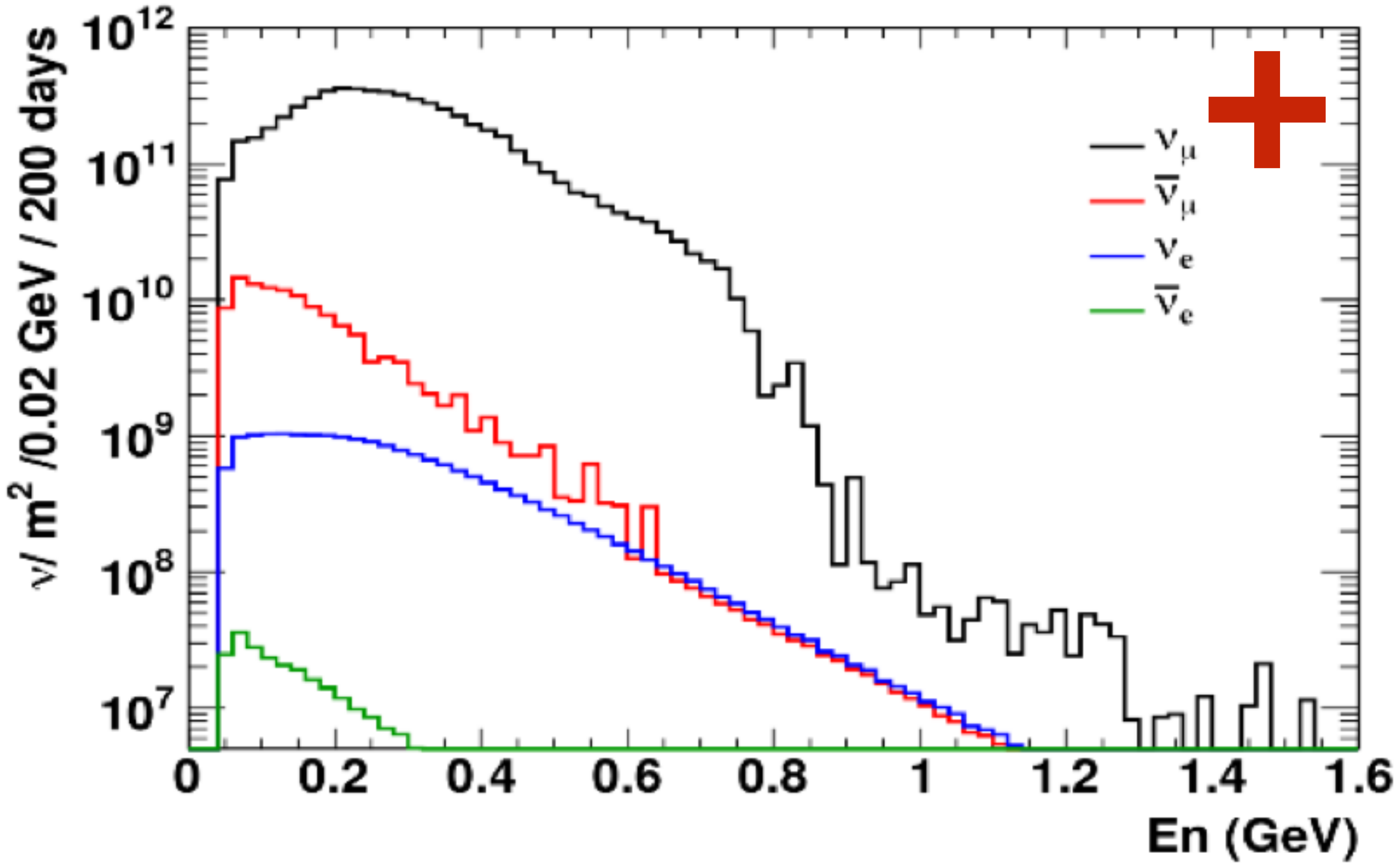


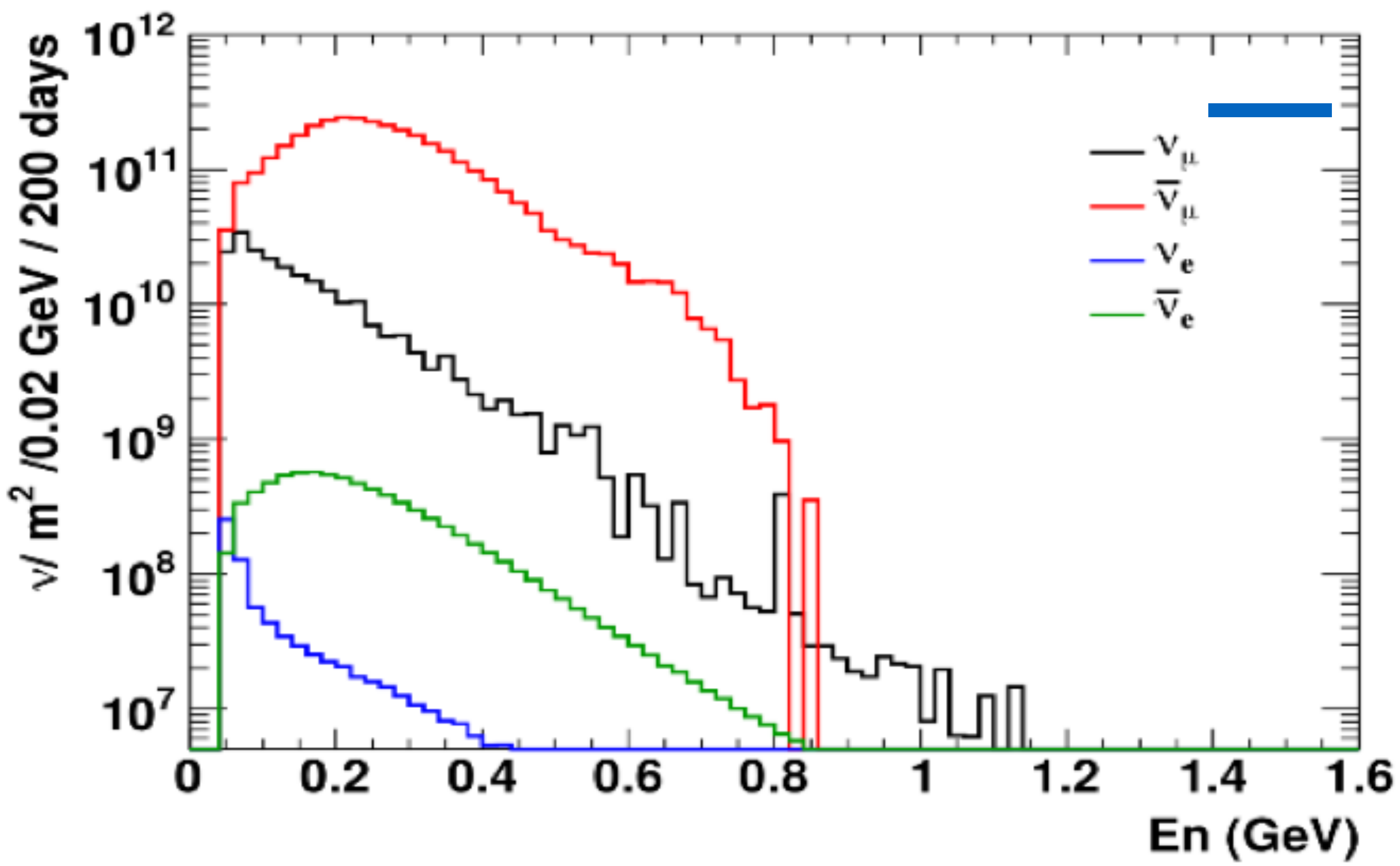
Horn parametrization based on Genetic Algorithm



Eric Baussan; and Packed-bed target, studied by RAL within the EUROnu project", Phys. Rev. ST Accel. Beams 17,031001 - arXiv: 1212.0732

ESSnuSB Neutrino Flux





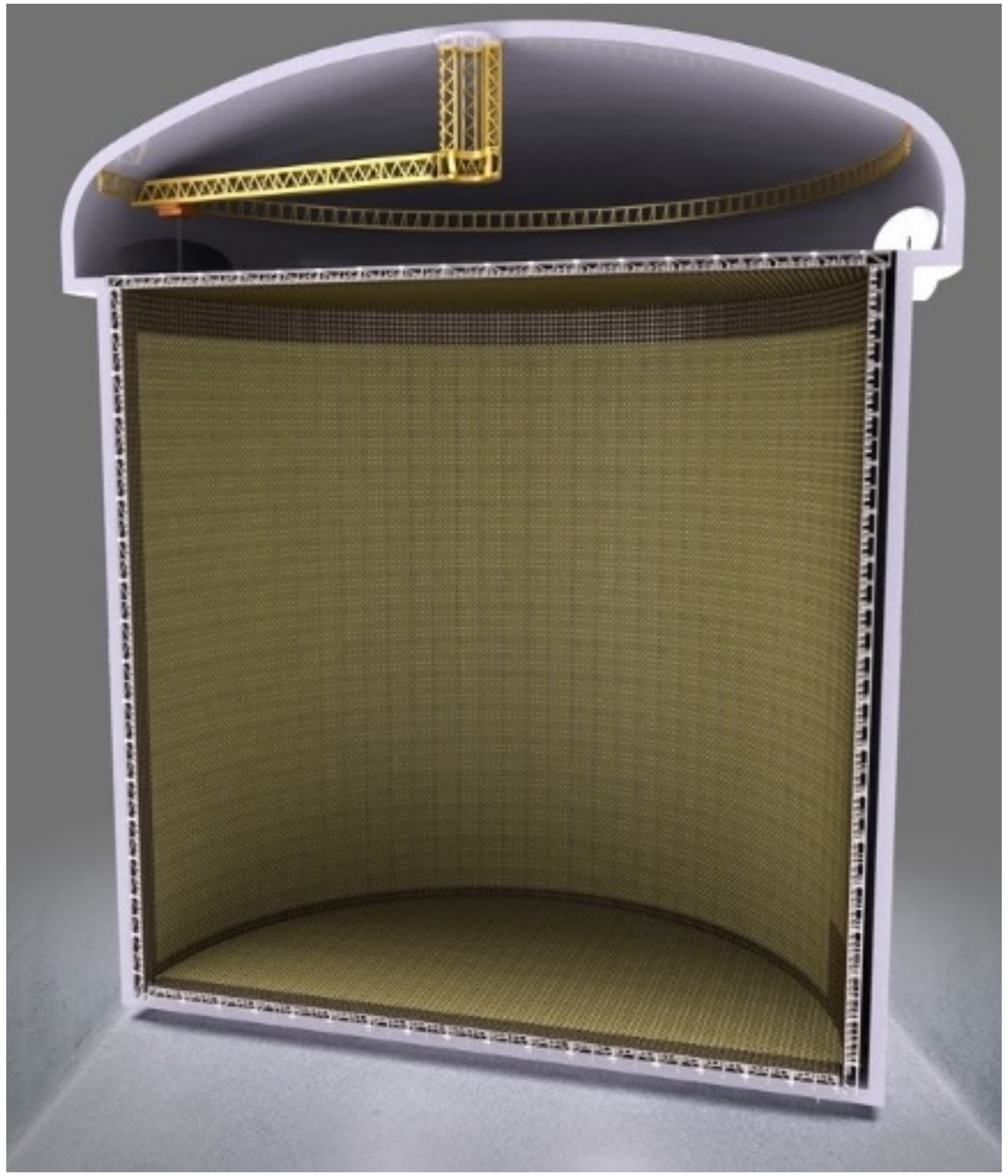
	Positive Polarity		Negative Polarity	
	N (1E10 1/m²)	%	N (1E10 1/m²)	%
Muon neutrino	583	98	23.9	6.55
Muon anti neutrino	12.8	2.1	340	93.2
Electron neutrino	1.93	0.3	0.08	0.02
Electron anti neutrino	0.03	0.01	0.78	0.21

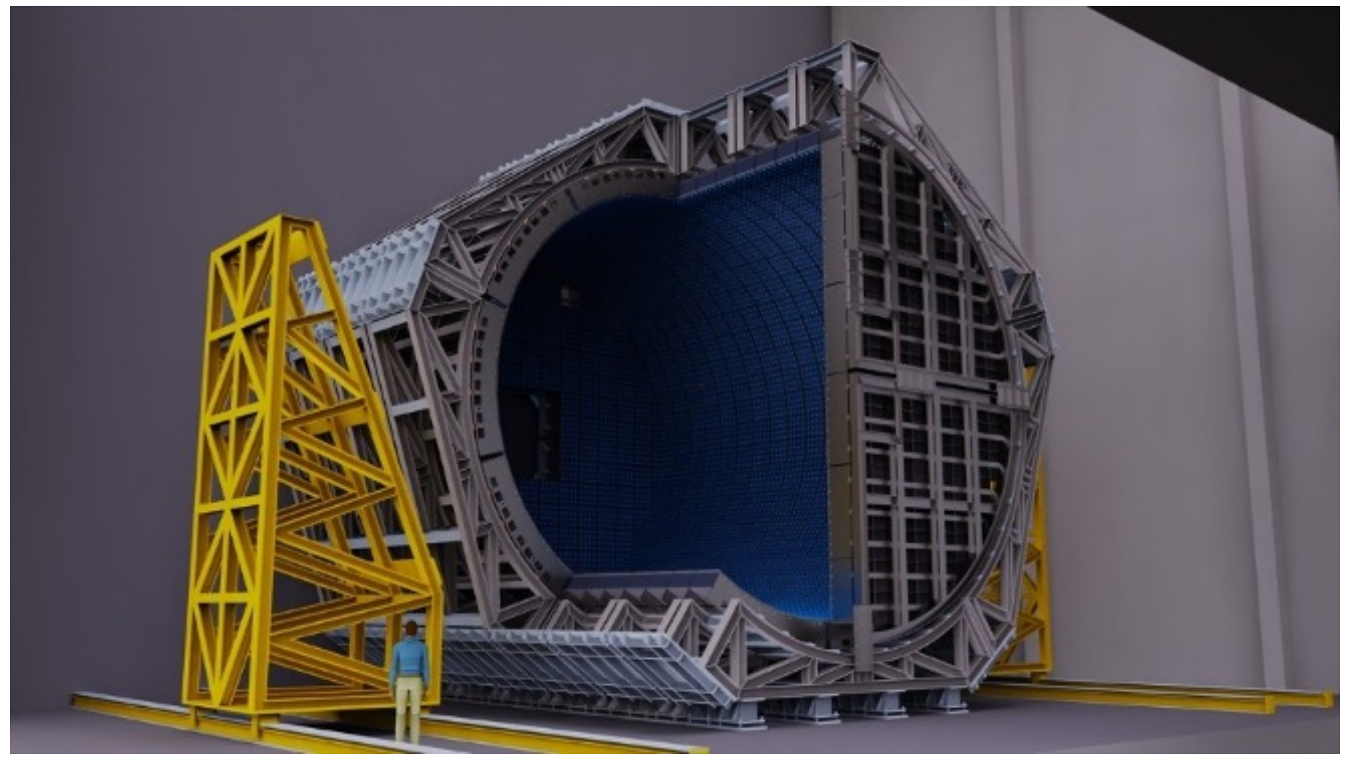
Eric Baussan

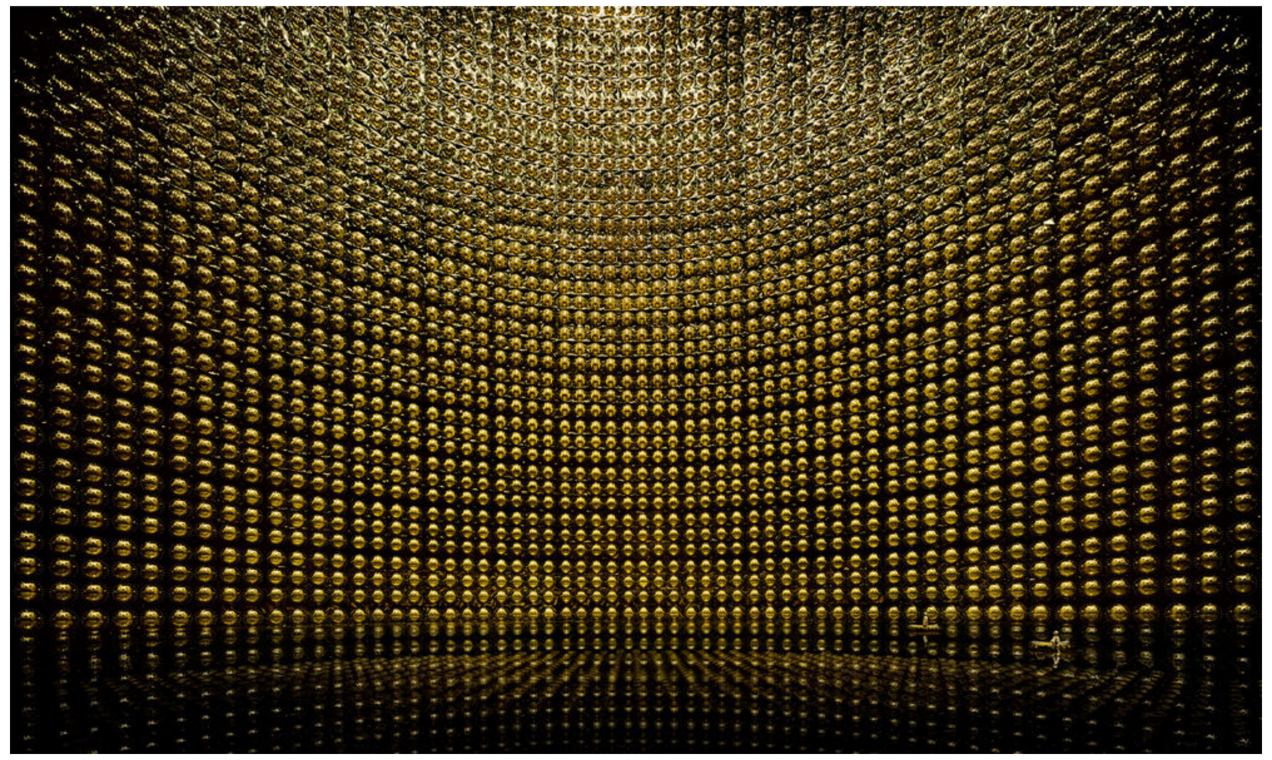
DETECTORS

Two water Cherenkov detectors:

- Far detector (370 km from target)
  - Pi x 37^2 x 74 m^3 >0.5 Megaton of ultra pure water as the far detector
    - That is 10 times the volume of the super-Kamiokande
    - 540k m^3 total fiducial volume
  - 100k 20” PMTs gives 40% coverage
  - 1500 meter deep underground
    - To decrease the noise and background from cosmic radiation
- Near detector (250 m from target)
  - Pi x 4.72^2 x 11 m^3







SUMMARY

- **The ESS project** has seen good progress, with RFQ beam commissioning completed
- **ESSnuSB** received funding to study the feasibility of ESS linac upgrade from 5 MW to 10 MW to deliver 1E23 p.o.t/yr for neutrino oscillation studies
  - **Linac upgrade**
    - The ESS linac lattice is capable of accelerating and transporting the H- beam with minimal stripping losses, such that the total losses of p and H- remain within 1 W/m
    - H- loss phenomena have been studied, and the transfer line to ring designed to respect the loss limits
    - The ESS's stacked multi-layer modulator has the capability to be upgraded for the ESSnuSB
  - **Accumulator**
    - A ring with 4 fold symmetry, collimation and RF section is designed to accumulate the high charge beam
    - Different injection paintings have been studied to manage the stripper foil heating and uniform charge distribution and a fast extraction system has been designed
  - **Target**
    - A target capable of receiving 4 x 1.6 MW, 2.5 GeV proton beam and a dedicated horn is designed
    - The power supply is designed to deliver high current short pulses (350 kA x 16 x 14 Hz)
  - Near and far detectors, cavern, civil engineering, and infrastructure were not covered in this talk

EUROPEAN SPALLATION SOURCE

THANK YOU!

Acknowledgments:

Most of the content is provided by my colleagues within the ESSnuSB collaboration, only some of the names are mentioned in the slides.

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ESSnuSB Looking for the answer

https://www.youtube.com/watch?v=PwzNzLQh-Dw
https://www.youtube.com/watch?v=qAnvft0nAlg