

# The Conceptual Design of the ESS

Steve Peggs,  
ESS & BNL





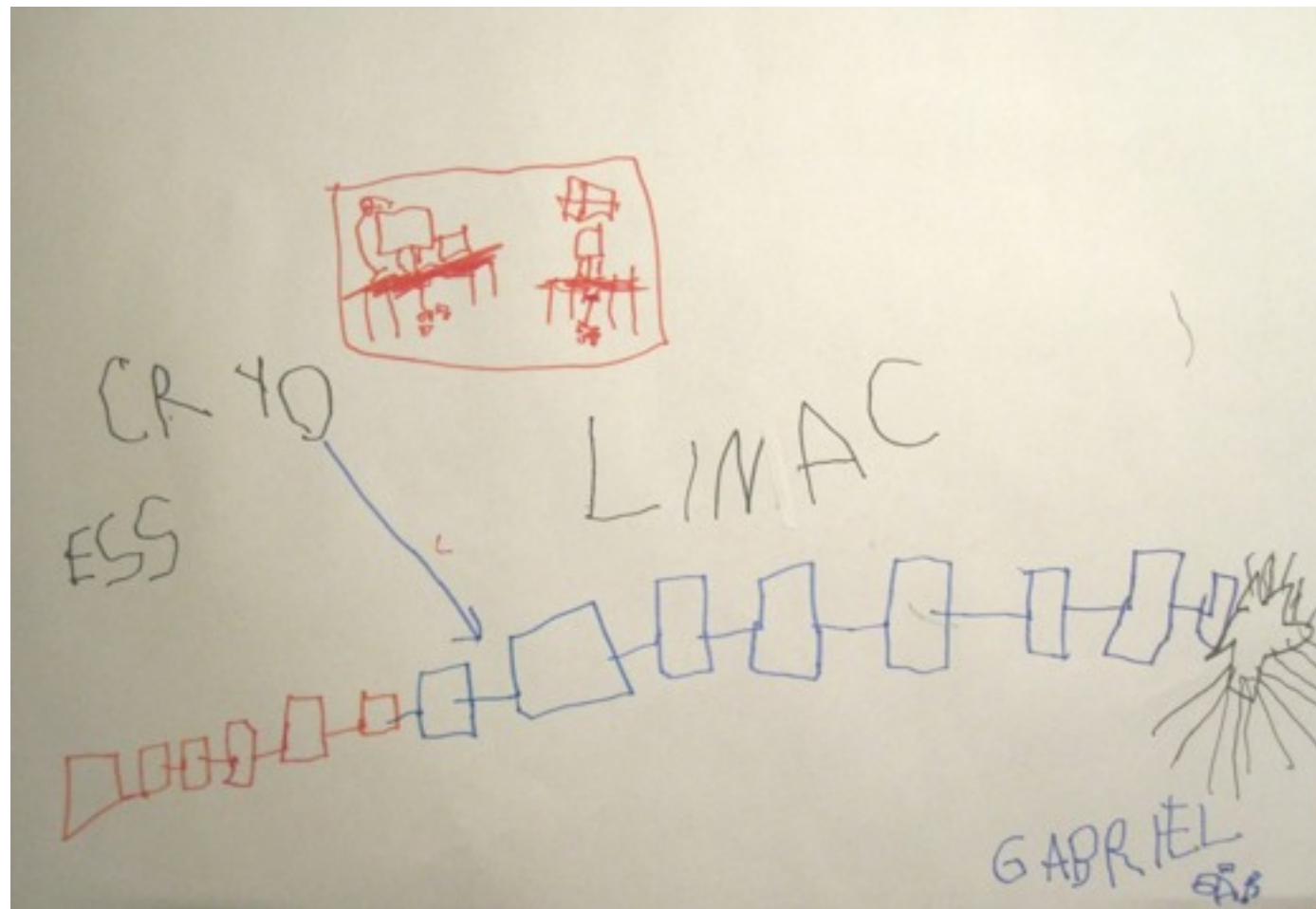
“Concept” to  
CDR (Feb 2012),  
TDR (Jan 2013),  
& on ....



ESS-2012-001  
6 FEB 2012

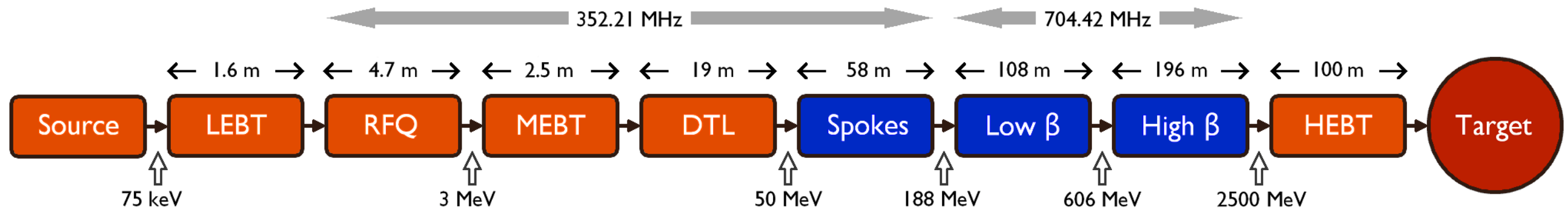
## Conceptual Design Report

Steve Peggs, Editor



European Spallation Source  
Lund  
2012

# Neutrons in 2019 !



5	MW	beam power
2.5	GeV	protons (H <sup>+</sup> )
2.9	ms	pulses
14	Hz	rep rate
50	mA	pulse current
704	MHz	RF frequency
< 1	W/m	beam losses
7.5	MW	upgradability?

NO H<sup>-</sup> injection, no accumulator/compressor ring !

# Q: Why ESS?

## A: Long pulses of cold neutrons

Many research reactors in Europe are aging & will close before 2020

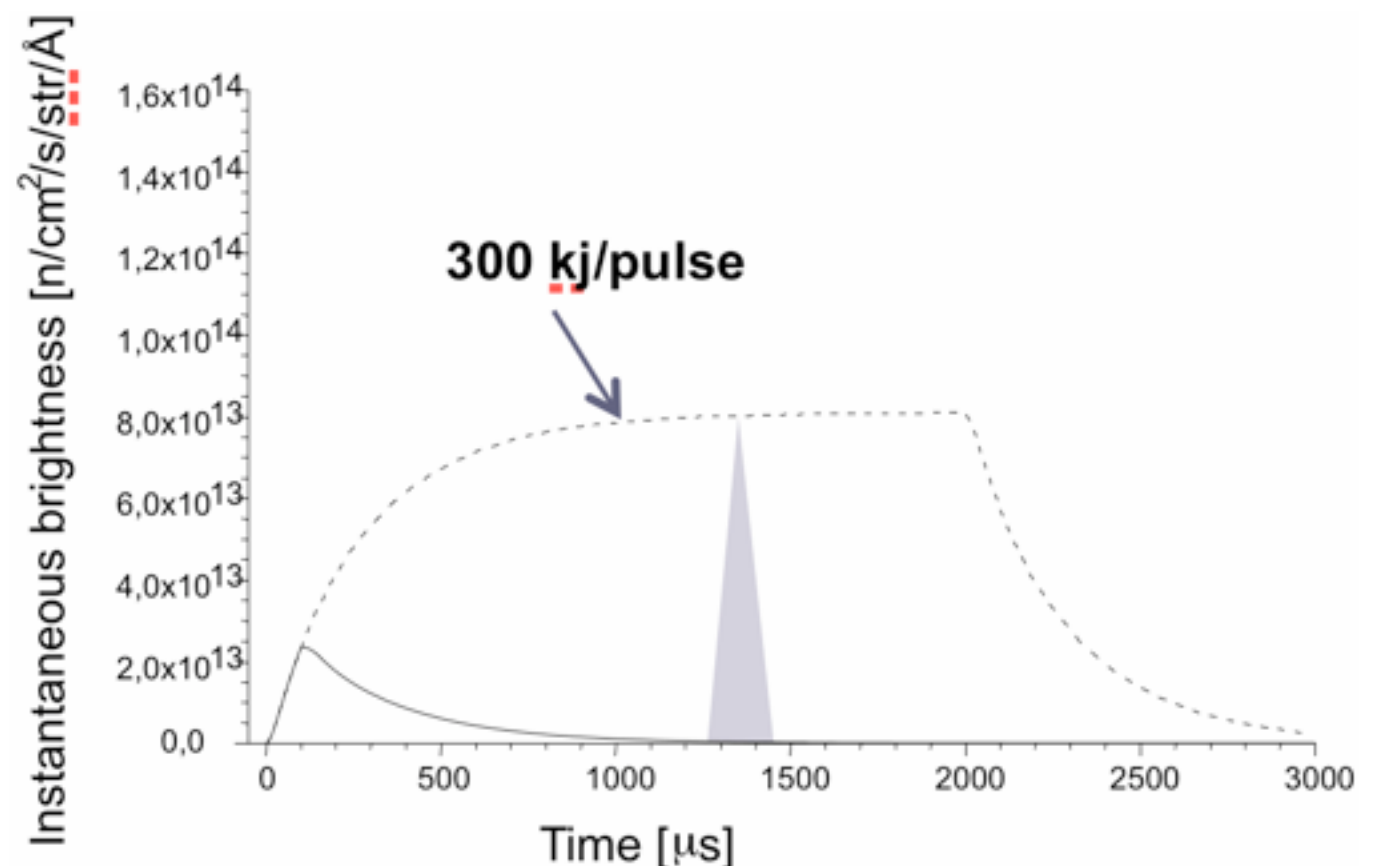
- Up to 90% of their use is with cold neutrons

There is a urgent need for a new high flux cold neutron source

- Most users are fully satisfied by a long pulse source
- Existing short pulse sources (ISIS, JPARC, SNS) can supply the present and imminent future need of short pulse users

*“Pulsed cold neutrons will always be long pulsed as a result of the moderation process”*

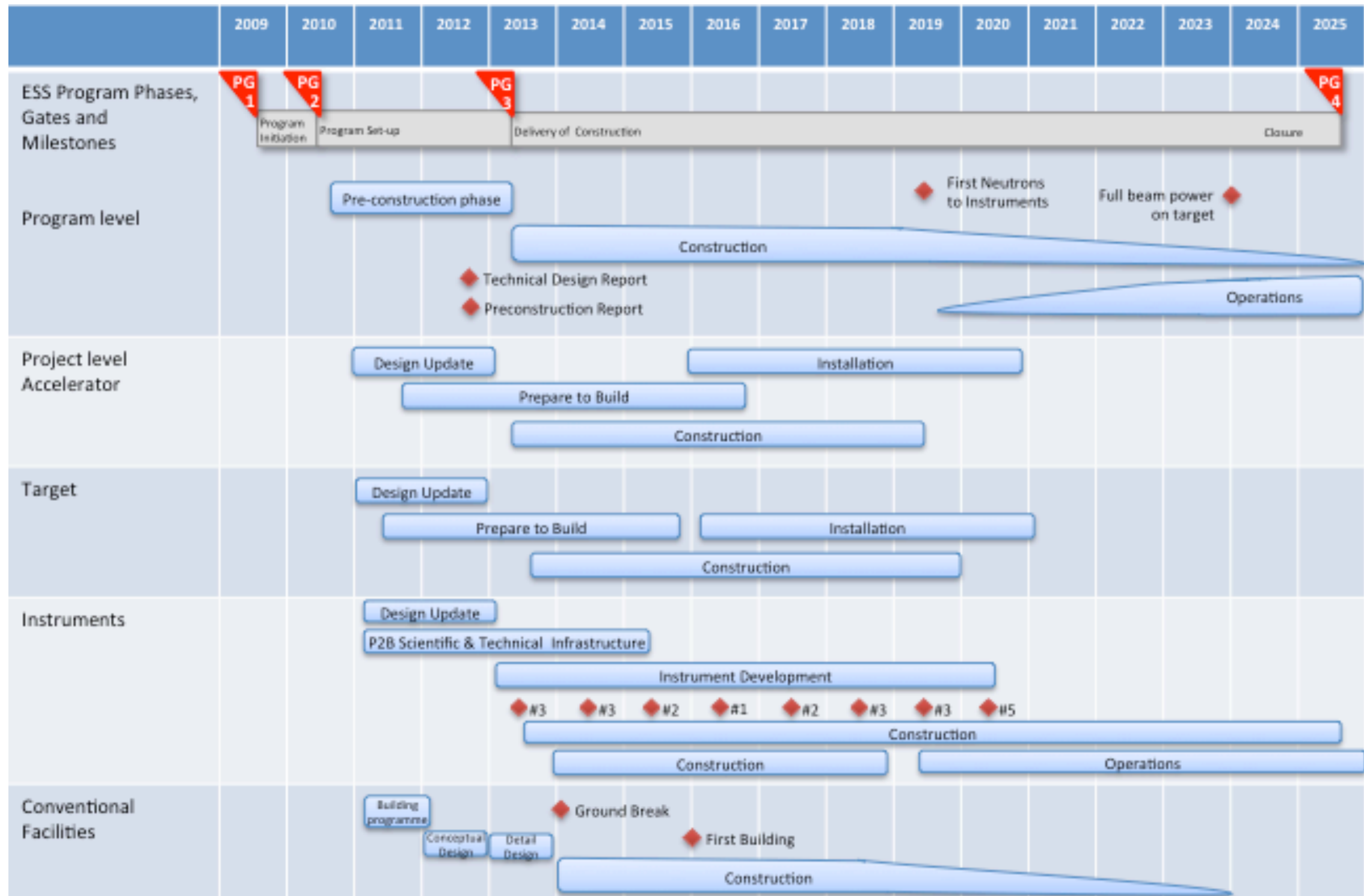
F. Mezei, NIM A, 2006



Steve Peggs



# Master schedule



F1: Design Update, Prepare to Build, Construction, & Operations phases

# The ESS site is in Sweden !

Sweden, Denmark & Norway cover 50% of cost



The **other 14 member states** covers the rest,  
with the European Investment Bank



# 2011 Fixed linac end & target

Note:

SWEREF coordinates

Ref.:1 Accelerator start

X: 134692.1

Y: 6179297.63

Ref.:2 Target station center

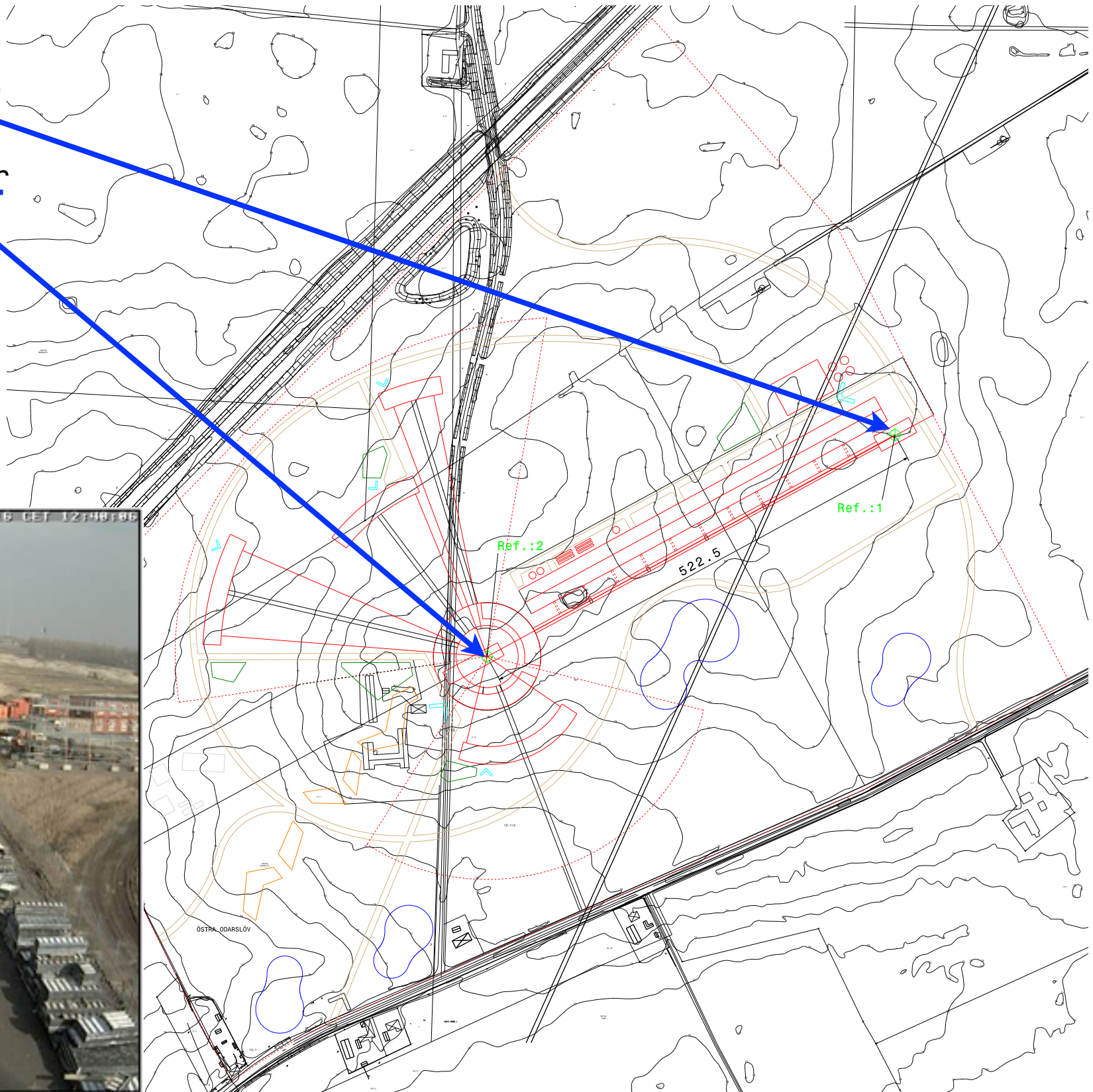
X: 134233.00

Y: 6179048.00

Max-IV under construction



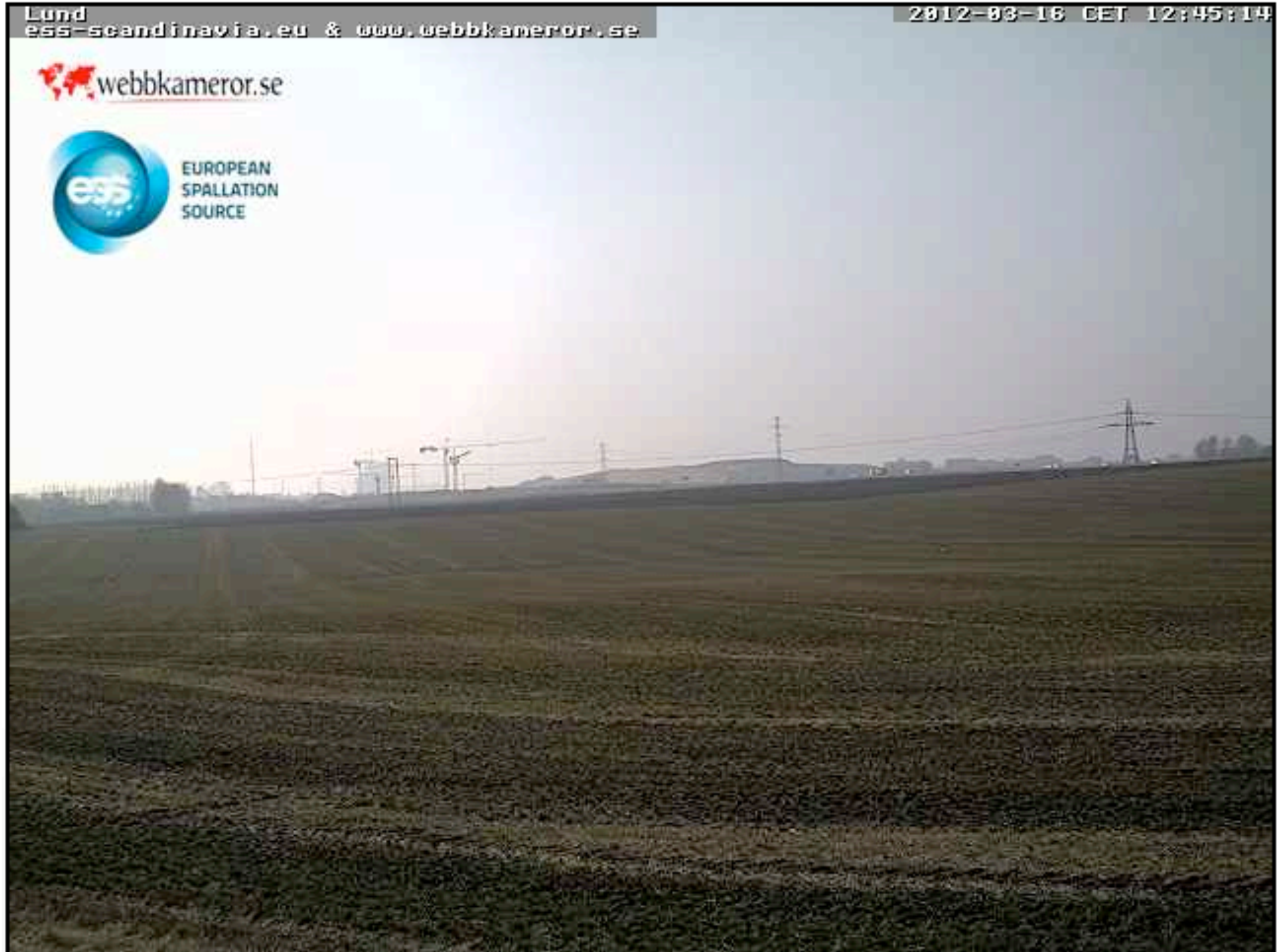
RAL+JAI, 120320



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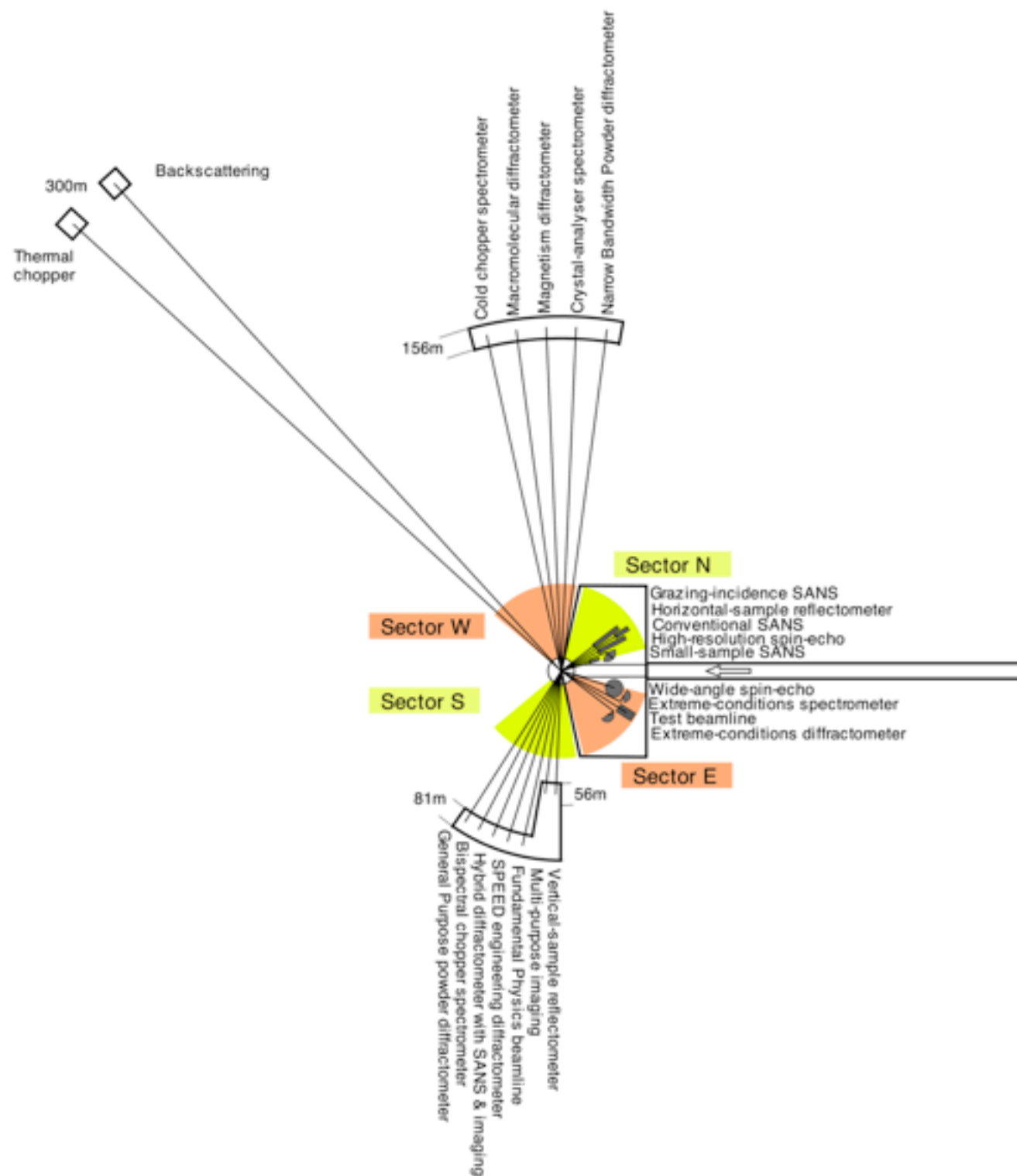


# The ESS green field



# Neutron Science

# Neutron lines

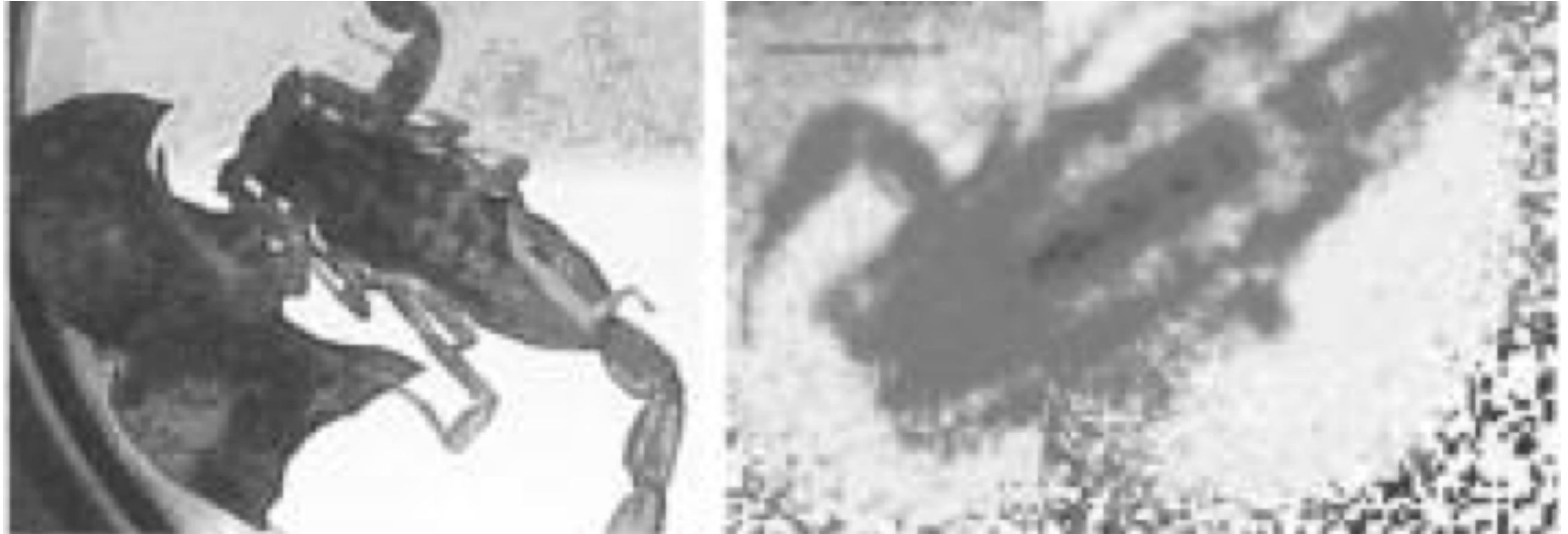


Sector	Port	Angle [deg]	Instrument name	Length [m]
EAST	1	-17.5	Wide angle spin echo	25+3
	2	-22.5	–	
	3	-27.5	Extreme conditions spectrometer	30+3+2
	4	-32.5	Test beamline	35+2
	5	-37.5	Extreme conditions diffractometer	25+3+2
	6	-42.5	–	
	7	-47.5	–	
	8	-52.5	–	
	9	-57.5	–	
	10	-62.5	–	
	11	-67.5	–	
	12	-72.5	–	
SOUTH	1	-82.5	–	
	2	-87.5	–	
	3	-92.5	Vertical sample reflectometer	56
	4	-97.5	Multi-purpose imaging	56
	5	-102.5	Fundamental Physics beamline	81
	6	-107.5	SPEED engineering diffractometer	81
	7	-112.5	Hybrid diffractometer with SANS & Imaging	81
	8	-117.5	Bispectral chopper spectrometer	81
	9	-122.5	General Purpose powder diffractometer	81
	10	-127.5	–	
	11	-132.5	–	
	12	-137.5	–	
NORTH	1	17.5	Small sample SANS	14+2
	2	22.5	High resolution spin echo	22+3
	3	27.5	Conventional SANS	20+12
	4	32.5	Horizontal sample reflectometer	30+5
	5	37.5	Grazing incidence SANS	20+12
	6	42.5	–	
	7	47.5	–	
	8	52.5	–	
	9	57.5	–	
	10	62.5	–	
	11	67.5	–	
	12	72.5	–	
WEST	1	82.5	Narrow Bandwidth Powder diffractometer	156
	2	87.5	Crystal analyser spectrometer	156
	3	92.5	Magnetism diffractometer	156
	4	97.5	Macromolecular diffractometer	156
	5	102.5	Cold chopper spectrometer	156
	6	107.5	–	
	7	112.5	–	
	8	117.5	–	
	9	122.5	–	
	10	127.5	–	
	11	132.5	Backscattering spectrometer	300
	12	137.5	Thermal chopper spectrometer	300

F5: Preliminary neutron beamline and instrument layout, for the instruments in T4.

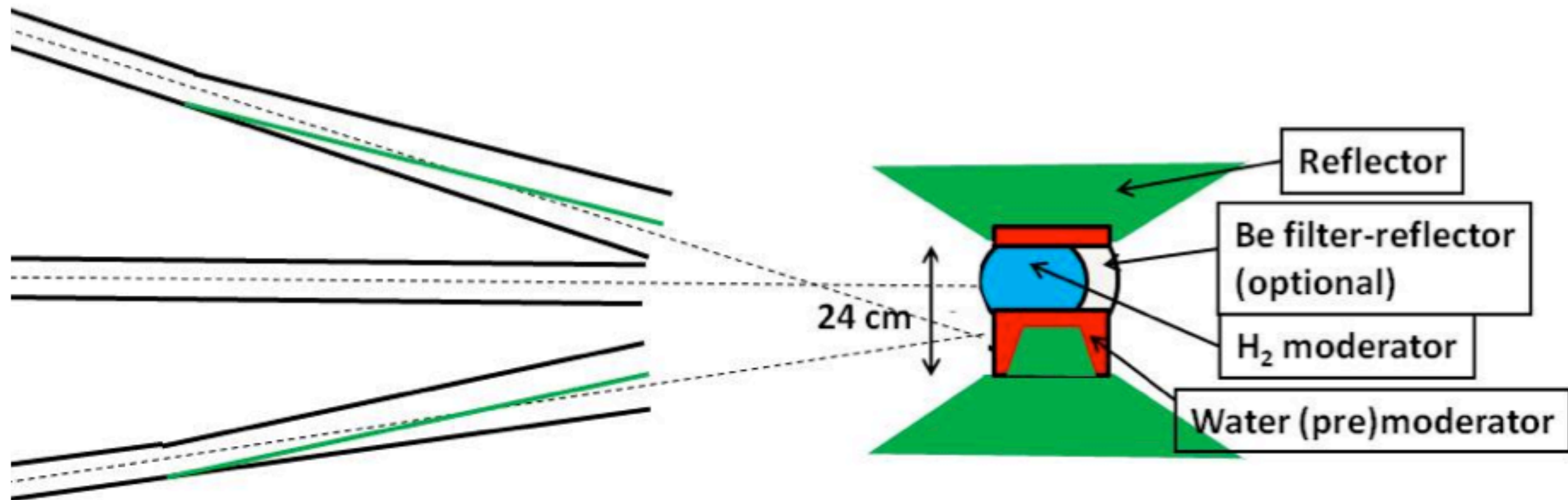


# Biology & imaging



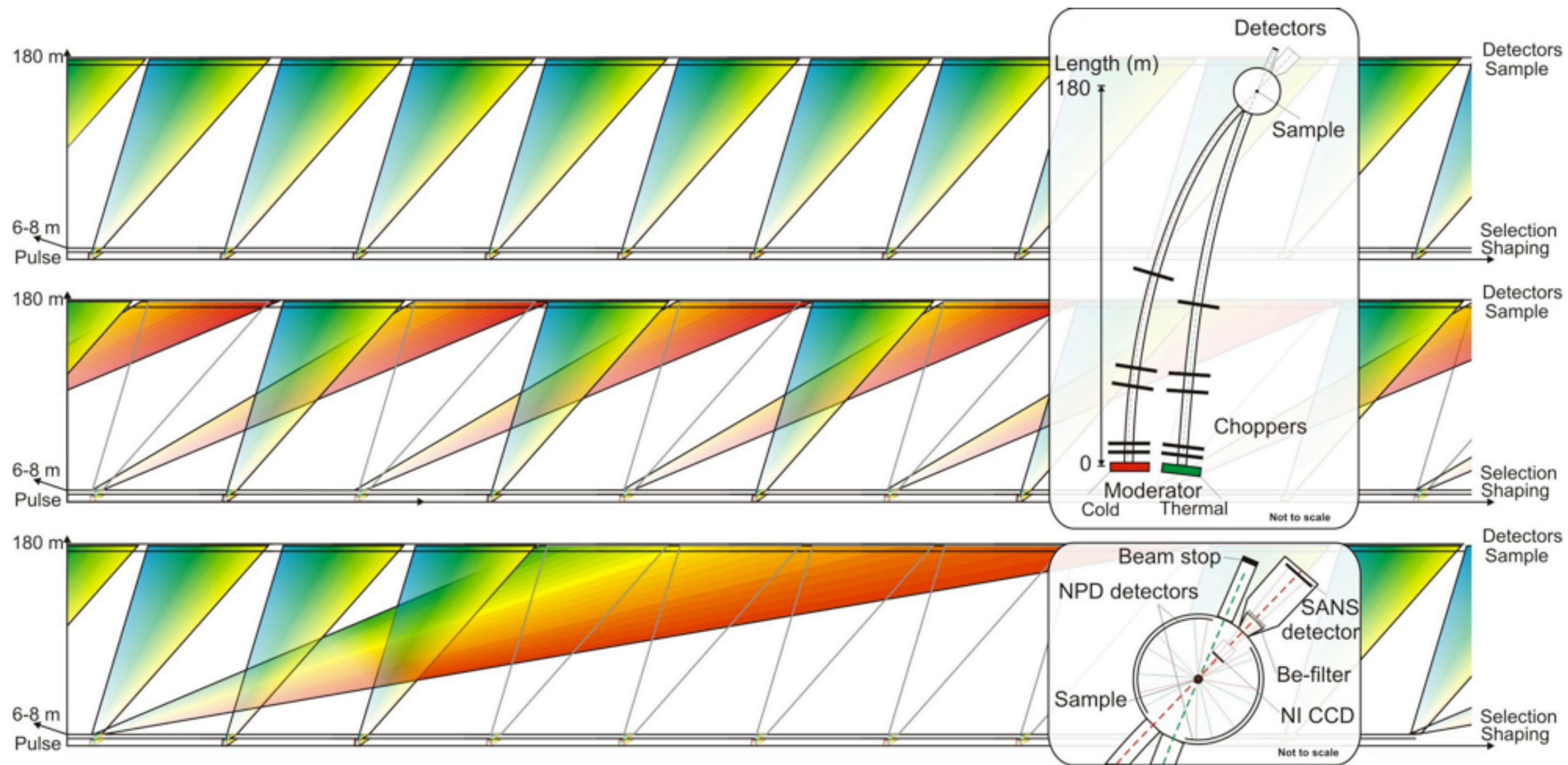
F27: Left: A scorpion and a leaf. Right: Neutron image of scorpion made from two stitched partial scorpion images at 10.0 Å and 300 seconds [60].

# Bi-spectral neutron beam extraction



F47: Plan view sketch of bi-spectral beam extraction. The two outer guides are bi-spectral, while the central one is purely cold. Not to scale.

# New concepts with long pulses

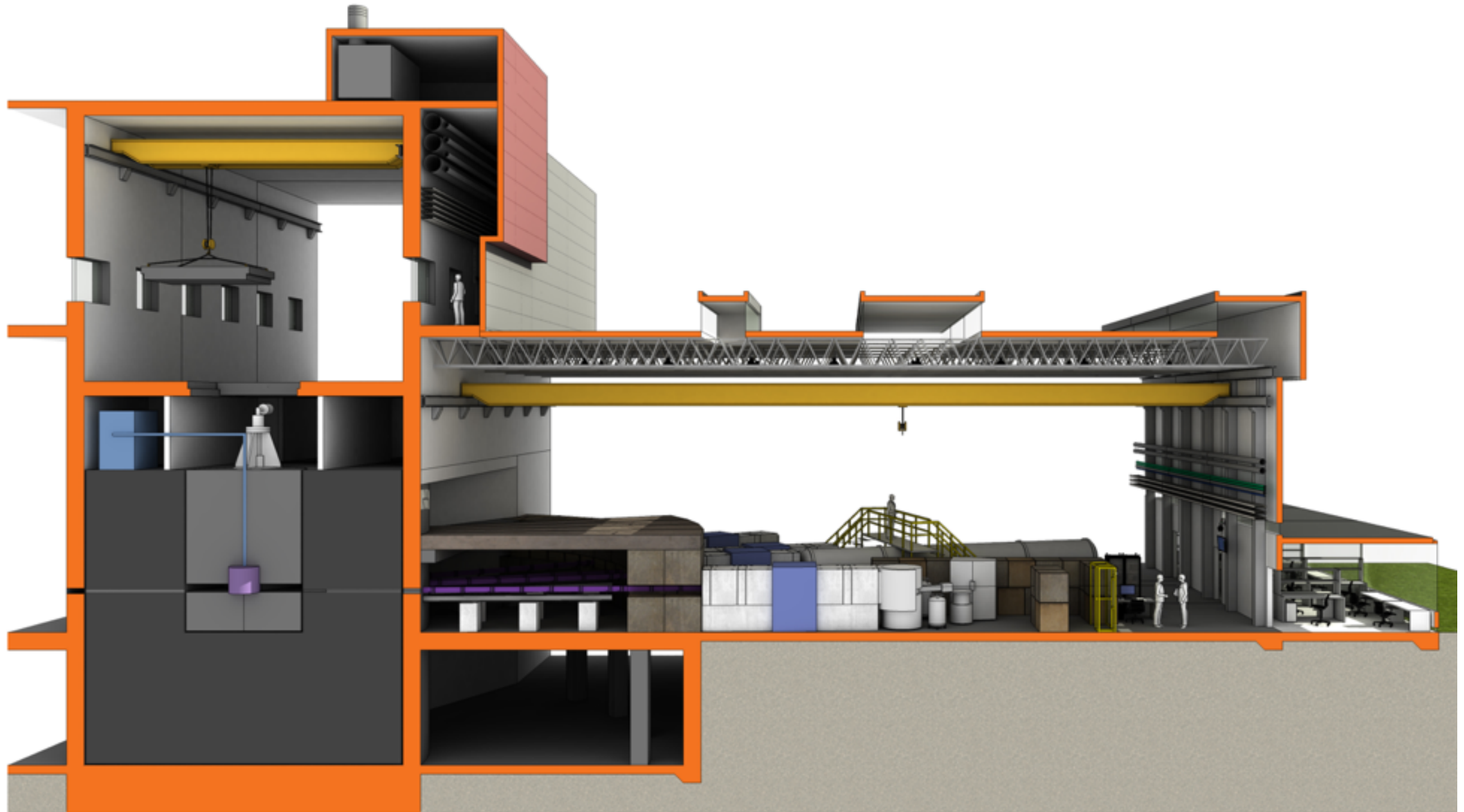


F15: Proposed time structure use and instrument layout using a dual cold and thermal guide system [37].



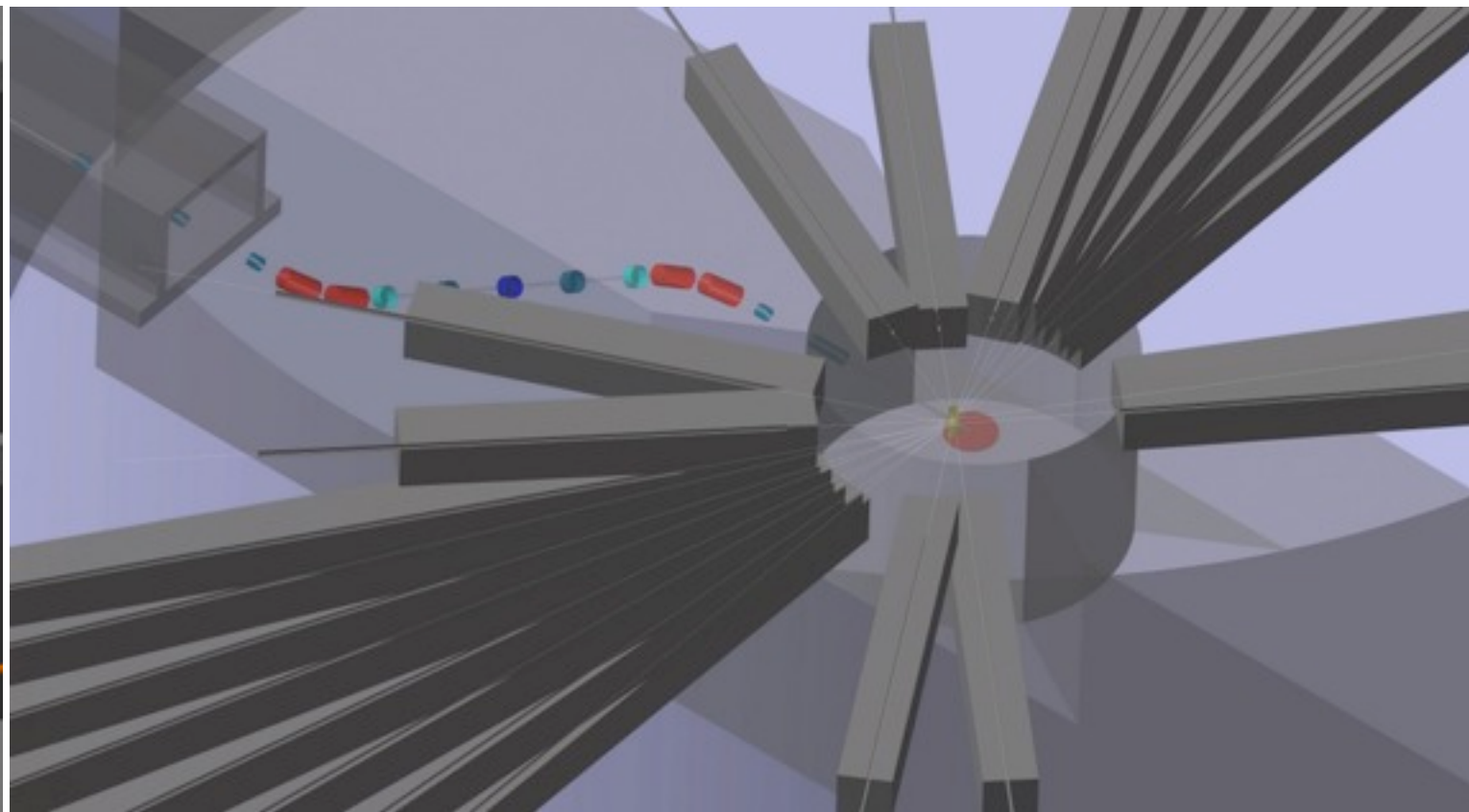
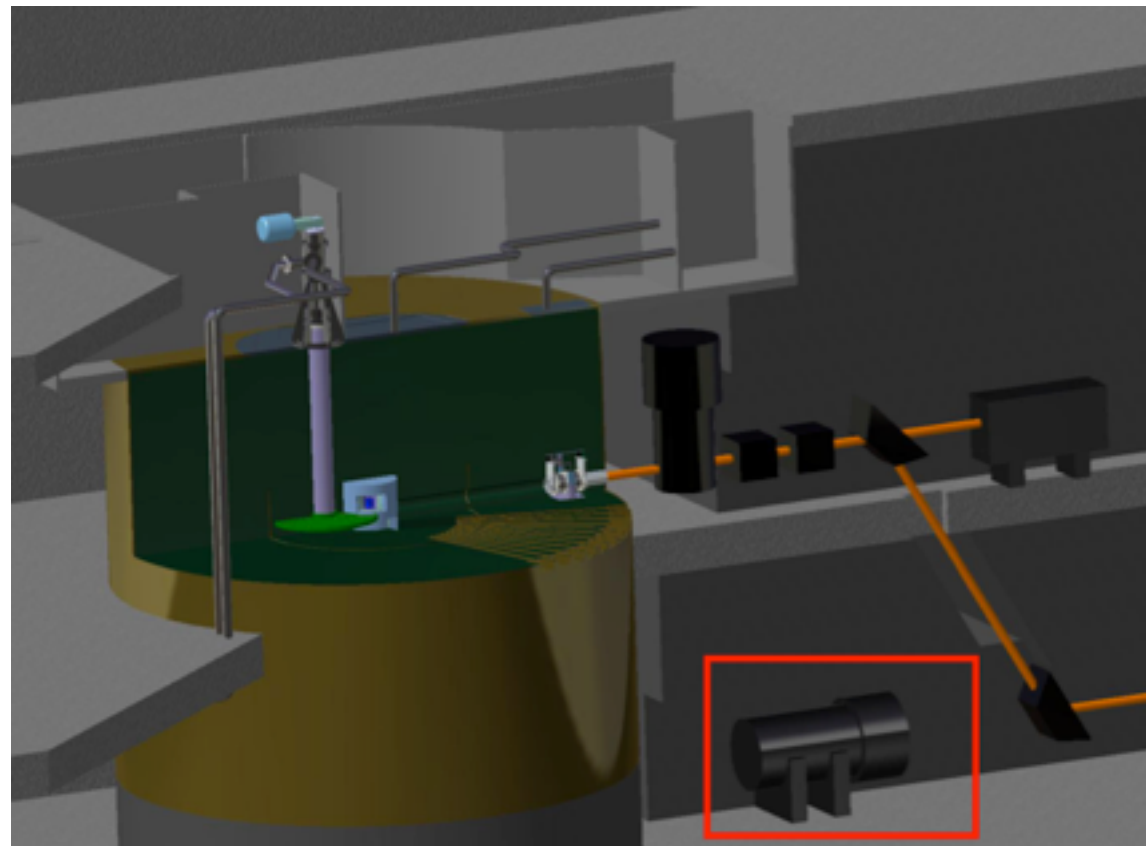
# Target Station

# Target station concept



F31: General conceptual layout of the target station. The target monolith is shown at the left, with representative neutron beamlines on the right.

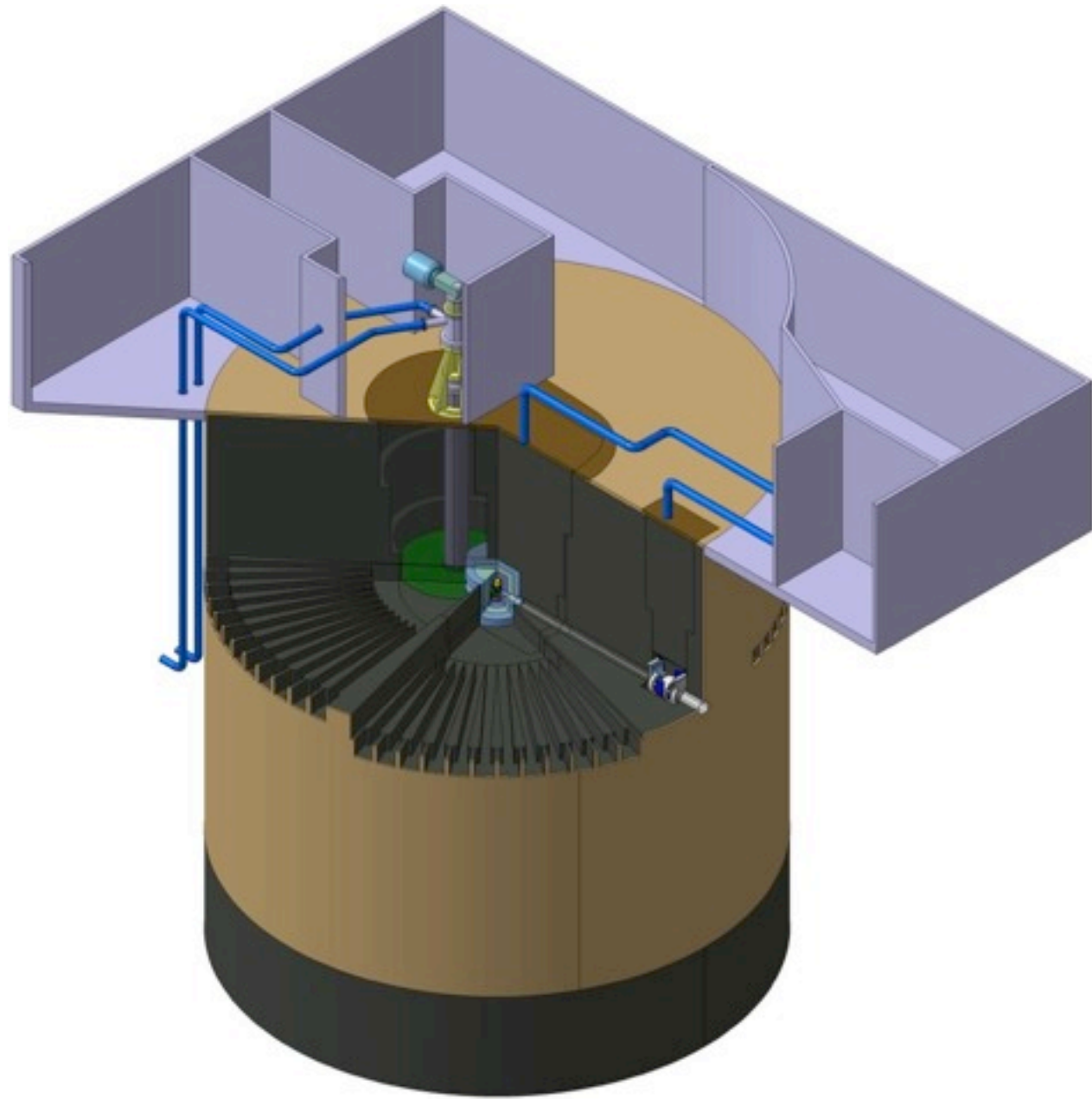
# Dog-leg



F56: Proton beam dump and neutron beam catcher in the target station building.



# Target-to-neutrons



How difficult can it be?

<http://www.youtube.com/watch?v=ijWwfcw0FOo>

Rotating tungsten disk target

- cooled by helium
- diameter 1.50 m
- thickness 0.08 m
- rotation rate 0.5 Hz

Target-to-neutron-lines

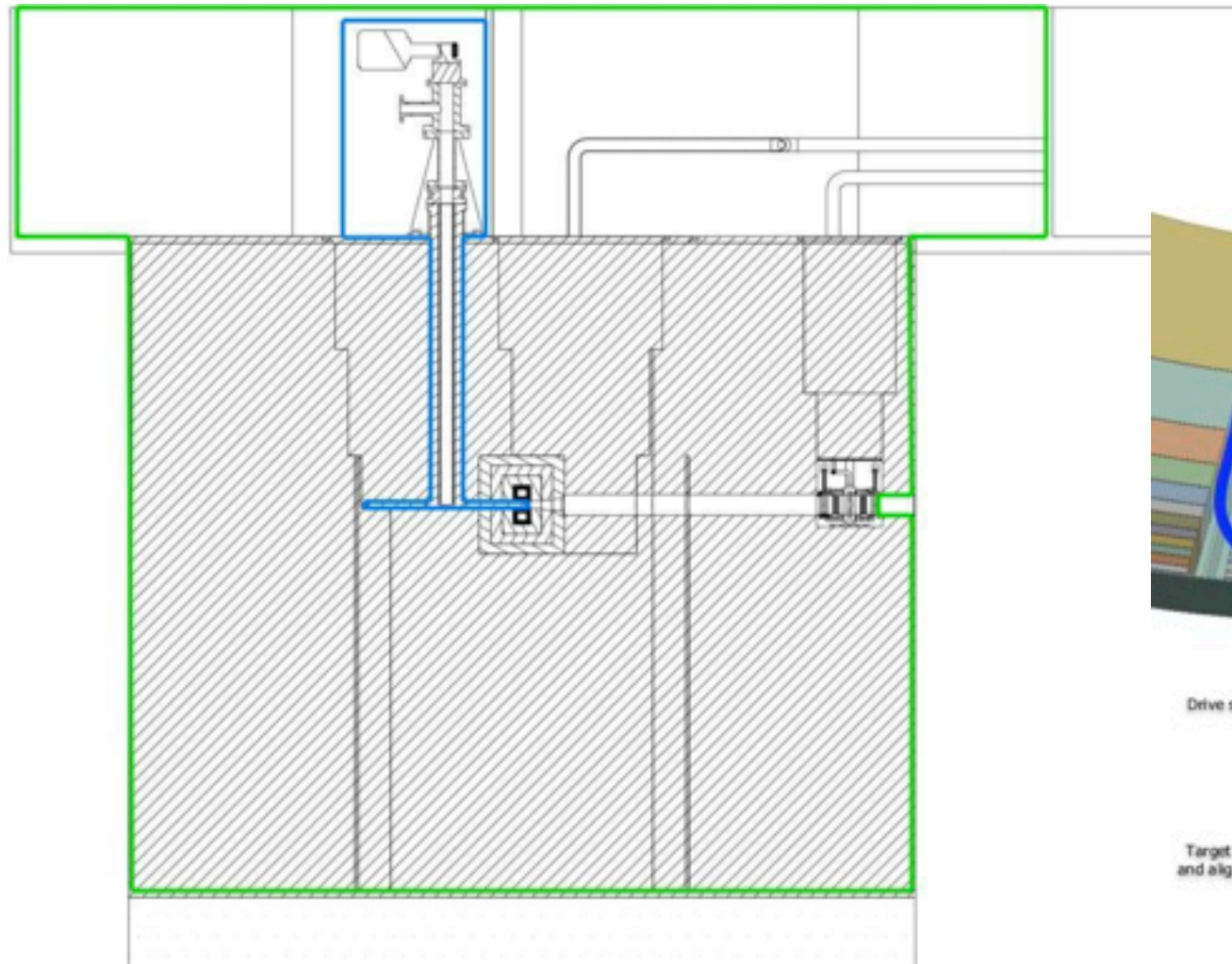
- 22 neutron lines
- Not all instruments commissioned on Day 1
- Moderators ~10 cm above & below target

F48: Target Station monolith general view.

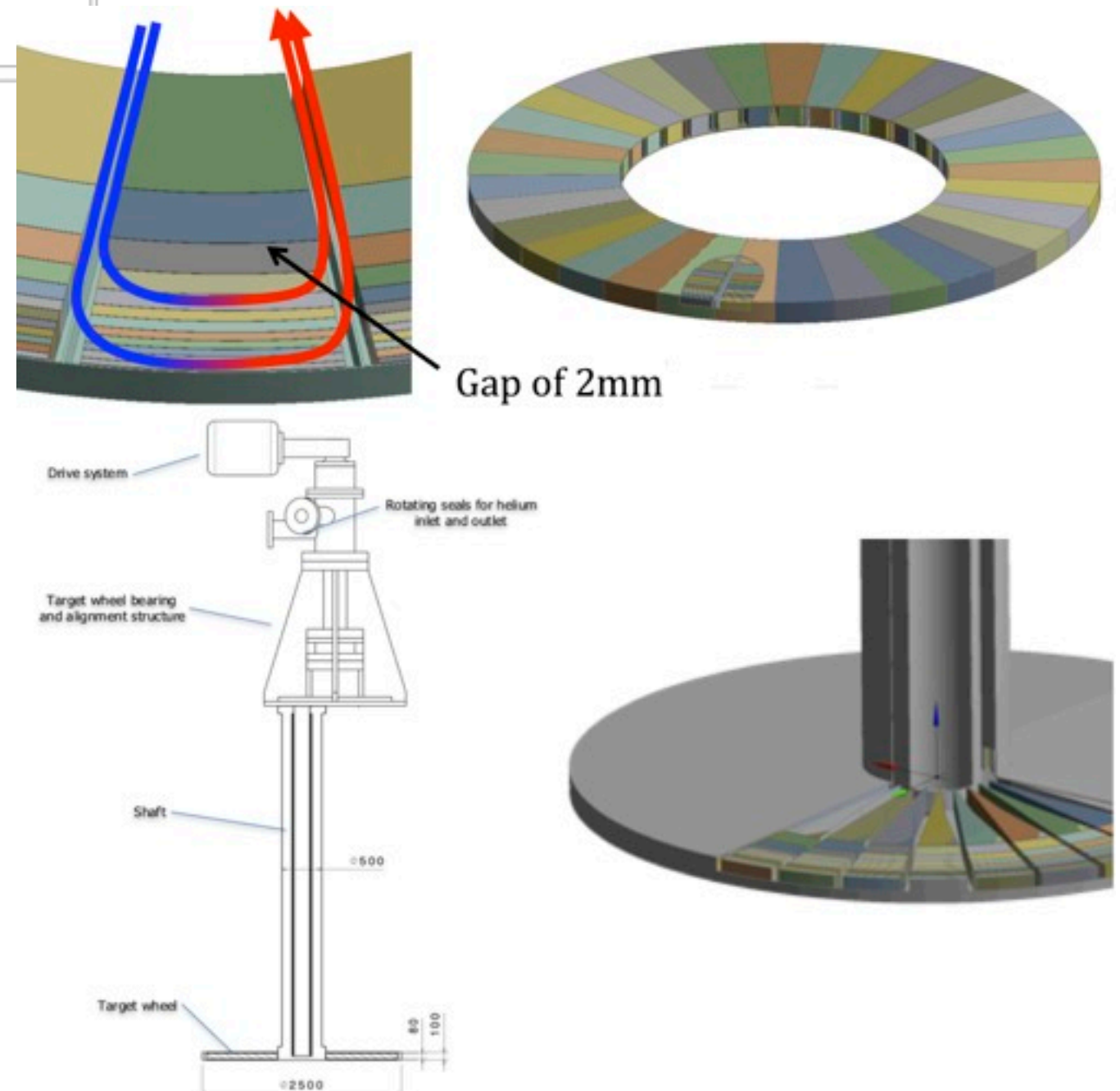
<http://esss.se/linac/Parameters.html>

# Rotating tungsten disk, helium cooled

F32: Sketches of the target wheel.  
Top: Radial and azimuthal flow of  
helium around the slices. Bottom:  
Global geometry, showing the  
angular sectorisation into slices.



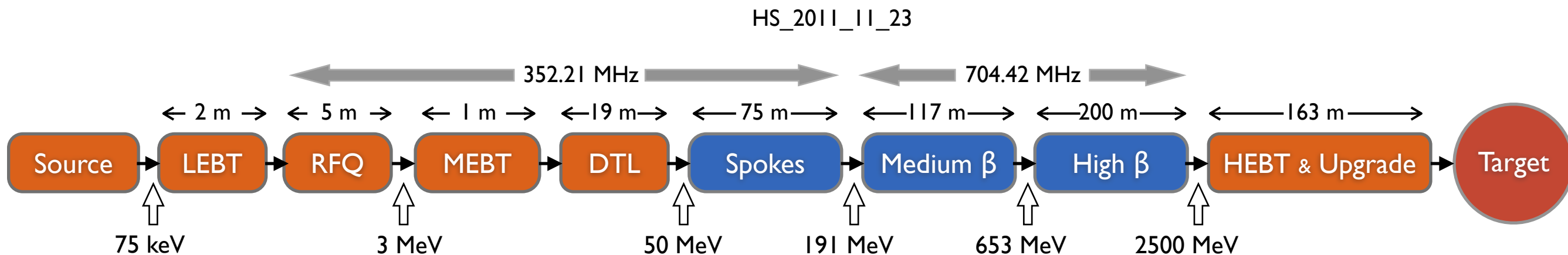
F49: Schematic view of the first  
(blue) and second (green)  
safety barrier locations during  
normal power operation.



# Accelerator



# Block diagram of HS\_2011\_11\_23 layout



Orange items (such as the RFQ and the DTL) are normal conducting.

Blue items (spoke resonators, medium & high- $\beta$  elliptical cavities) superconducting.

2012 decisions, evolving beyond HS\_2011\_11\_23::

- Segmented layout of the superconducting linac with warm quadrupoles
- Transition energy from DTL to spoke cavities increased to about 80 MeV
- Upgrade current 100 mA (for distant future!)
- DTL designed for 50 mA

Decisions about RFQ length, RFQ design current & MEBT design under way

# Upgrade guideline

The upgrade guideline states that a power upgrade can be made by increadsing:

- the beam current up to maximum 100 mA
- the proton energy up to 3.5 GeV.

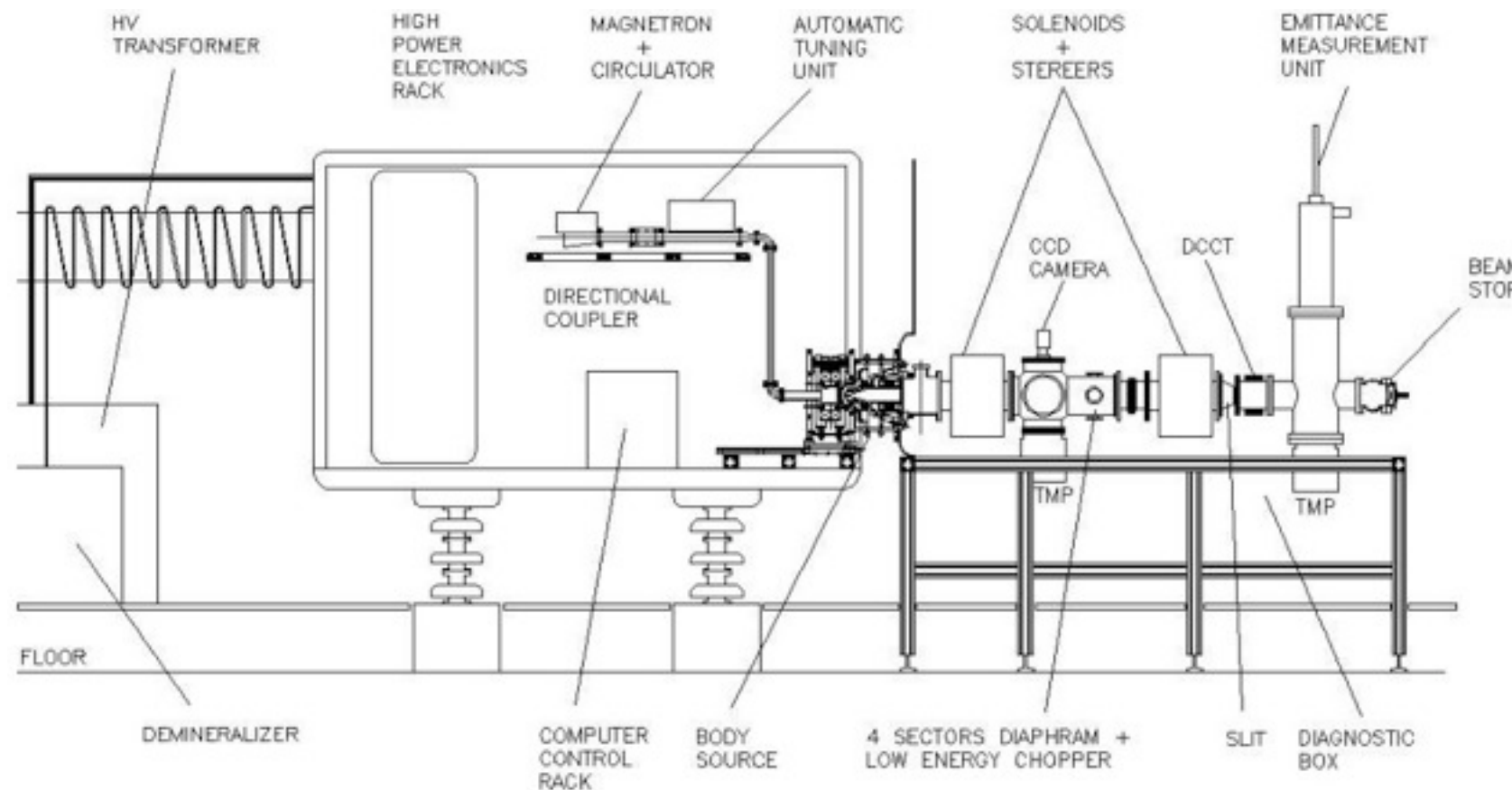
For the superconducting linac, the current can be doubled from 50 mA to 100 mA without changing the basic layout **if** the power of all RF sources can be doubled.

Doubling the power of the RF sources can be done, in principle, by:

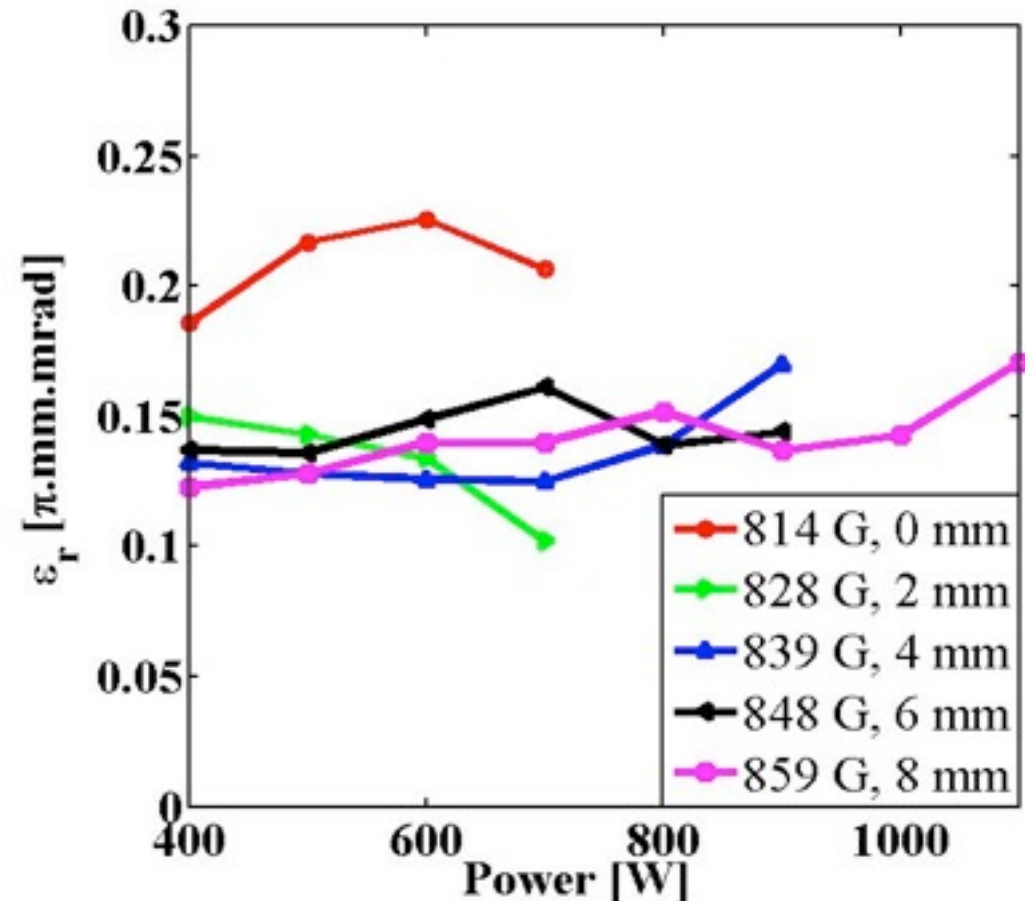
- connecting “old” klystrons 2-by-2 to half of the cavities, &
- new klystrons, twice as powerful to remaining cavities

# Source & LEBT

Degree of development is already consistent with the ESS specs, i.e. nearly ready for a TDR.



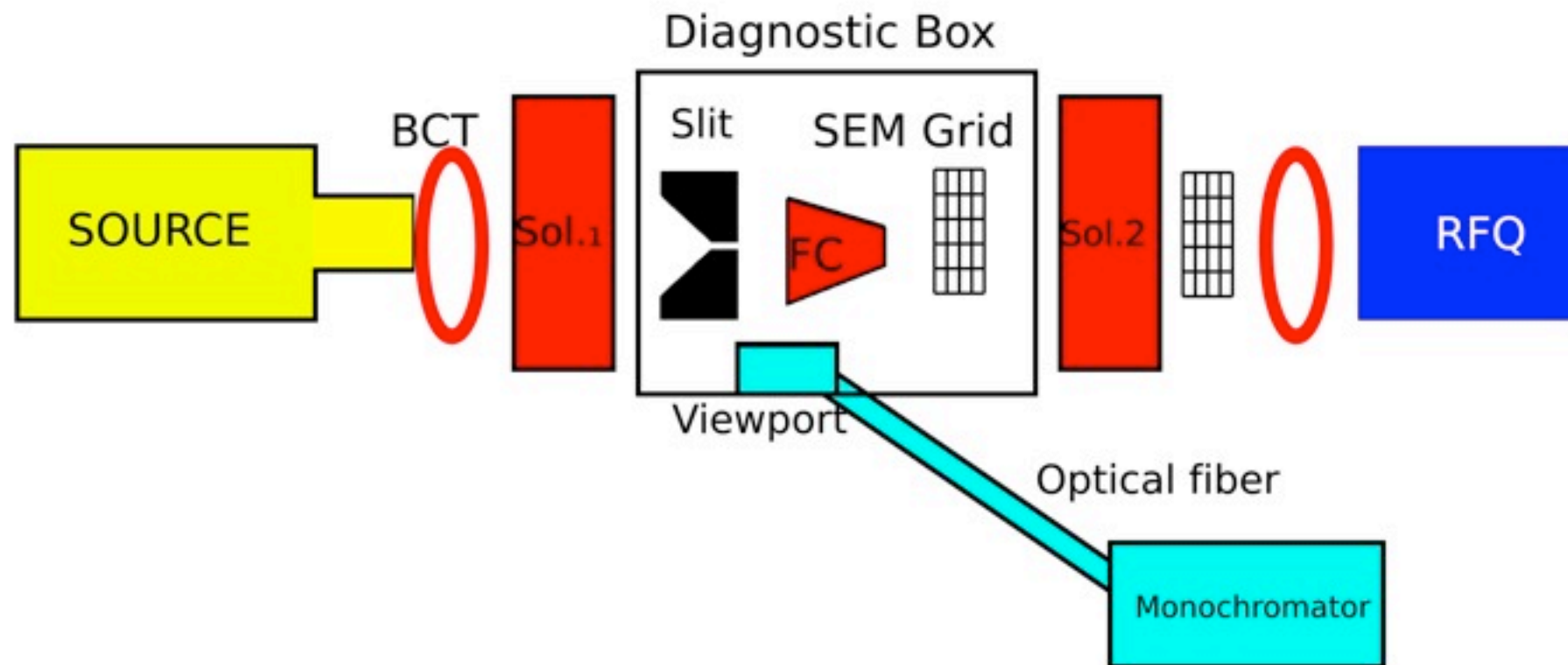
F68: Schematic layout of the ion source & Low Energy Beam Transport.



F69: Measured ion source emittances for different values of microwave power and magnetic field.



# LEBT



## Beam Instrumentation:

- Current measurement with 2 BCTs and one Faraday cup
- Beam profile with 2 SEM grids (H+V)
- Emittance msmt with Slit and grid system (grid used also for profile measurement)
- Ions species fraction: Viewport +monochromator

# RFQ

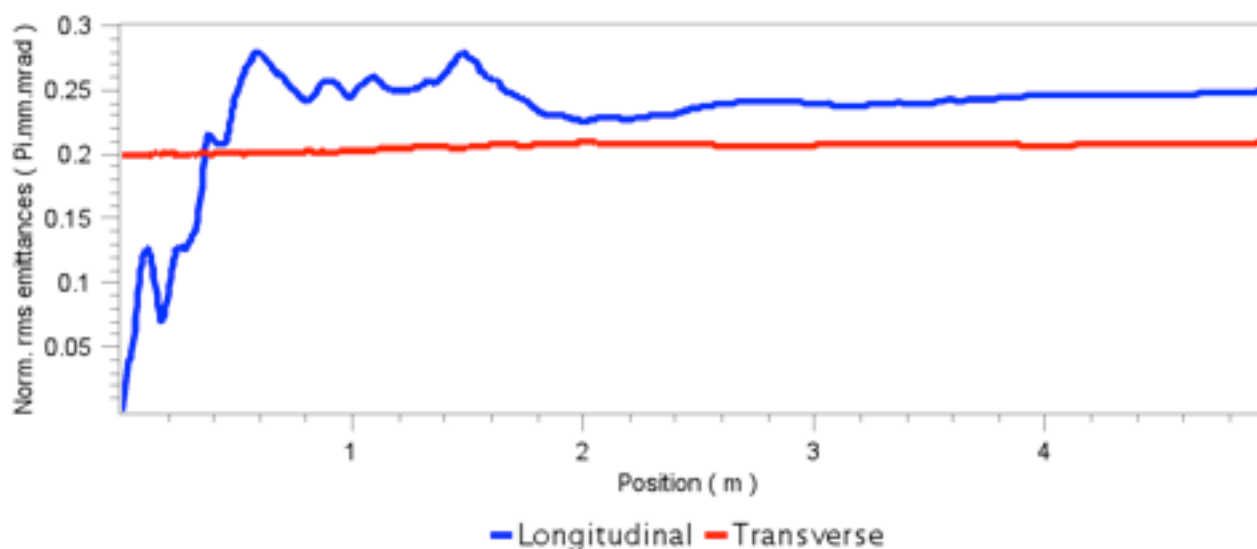
Beam dynamics design at a rather advanced stage, but cross-check with more simulation codes; perform error analysis.

Engineering design will be finished for the TDR

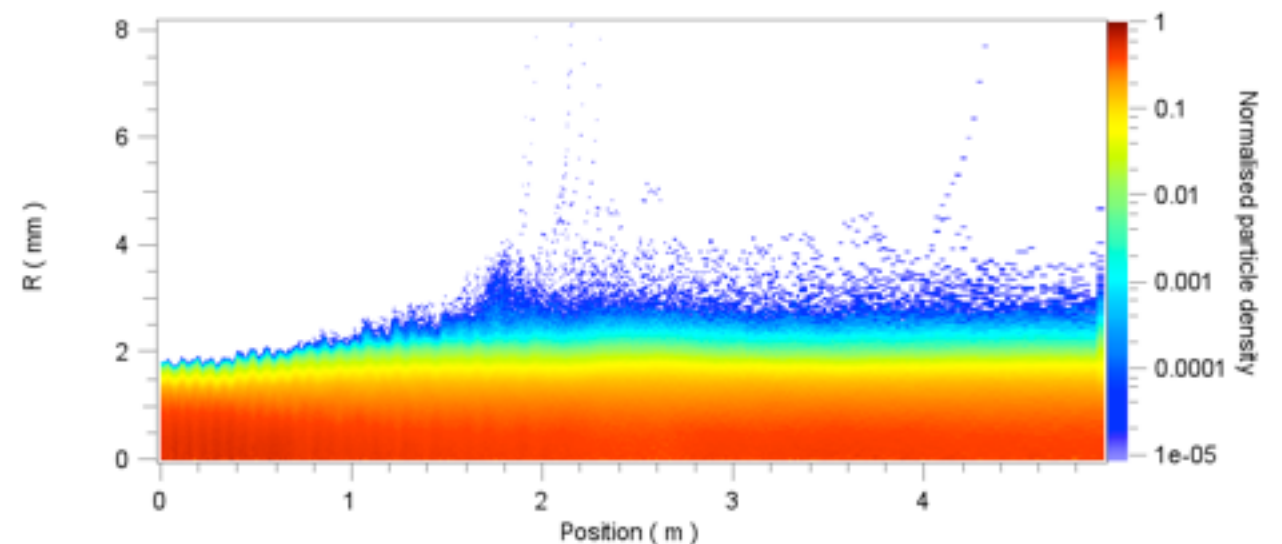
Issue: RFQ length: as designed 5 m

**Long** RFQ: small  $\epsilon L$  increase & high T. Is a smaller emittance a substantial reliability issue, compared with drawbacks?

**Shorter** RFQ (3 m): fewer brazing/vacuum/cooling joints; less RF power; less expensive, easier to achieve requested tolerances.



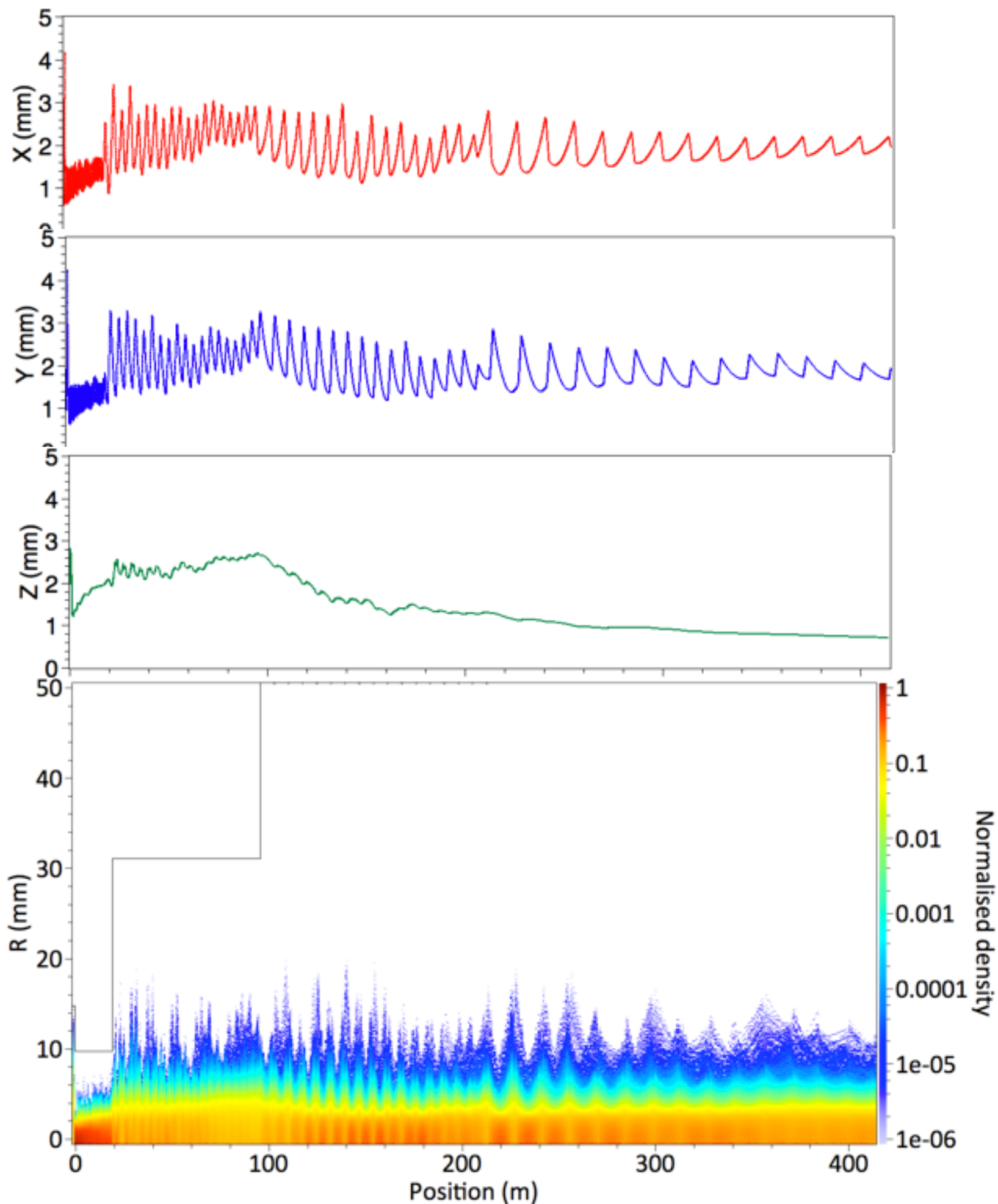
F60: Emittance through RFQ.



F61: Radial particle density distribution as a function of radius and distance along the RFQ.

# RFQ - 2

F62: RMS beam sizes in the HS\_2011\_11\_23 lattice, from RFQ to the last elliptical cavity, for an initial  $0.20 \pi$  mm mrad 4D waterbag distribution without space charge.

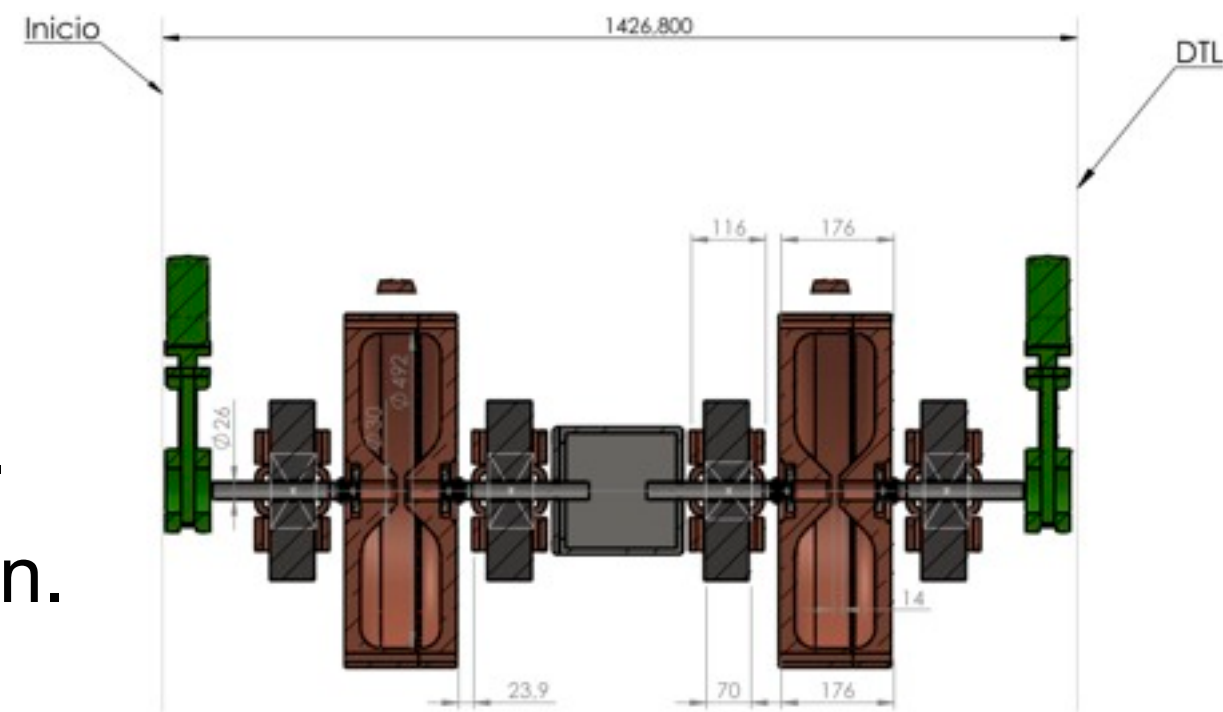


F63: Transverse particle density distribution along the HS 2011 11 23 linac, with the black contour representing the clear aperture.

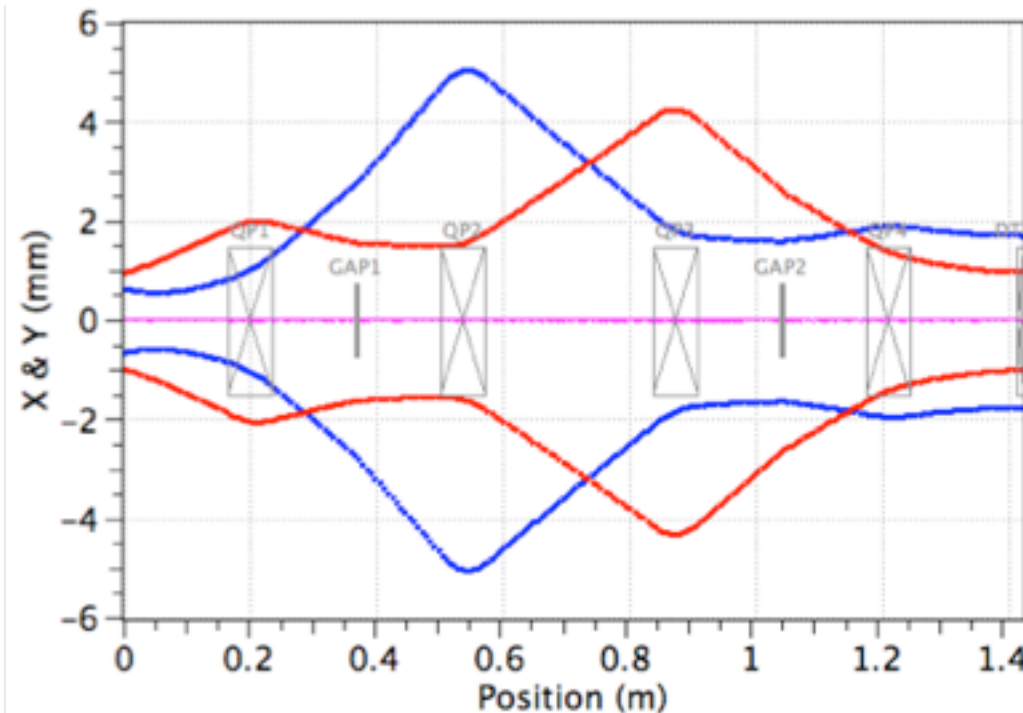
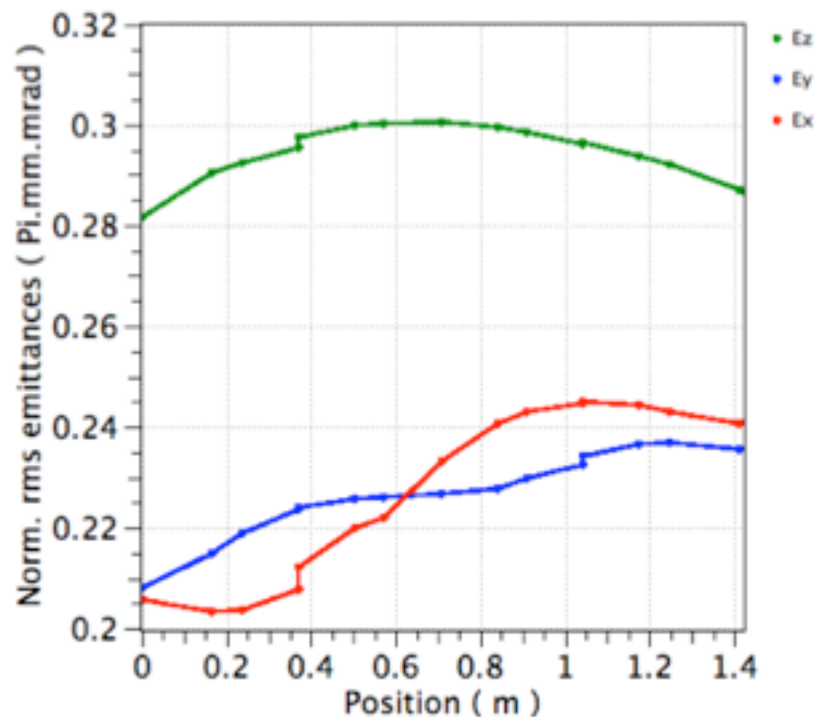


# MEBT

There is no realistic MEBT design yet.  
MEBT induces some emittance growth.  
MEBT enables chopping and collimation.  
Recent decision to go “full function”  
Prototype where? Beam tests?

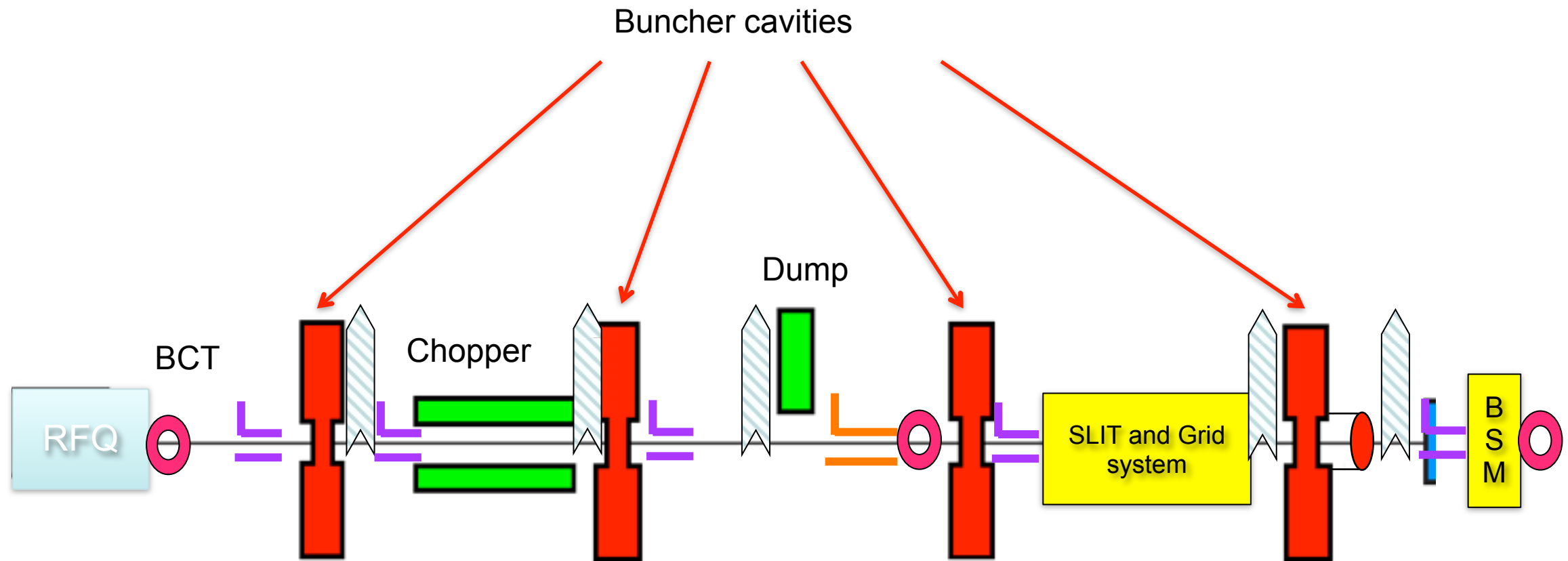


F71: Compact MEBT layout, with 4 quadrupoles & 2 buncher cavs



F72: Left: Emittance growth through the MEBT in the horizontal (red), vertical (blue) and longitudinal (green) planes. Right: RMS beam size envelopes.

# MEBT instrumentation (tentative)

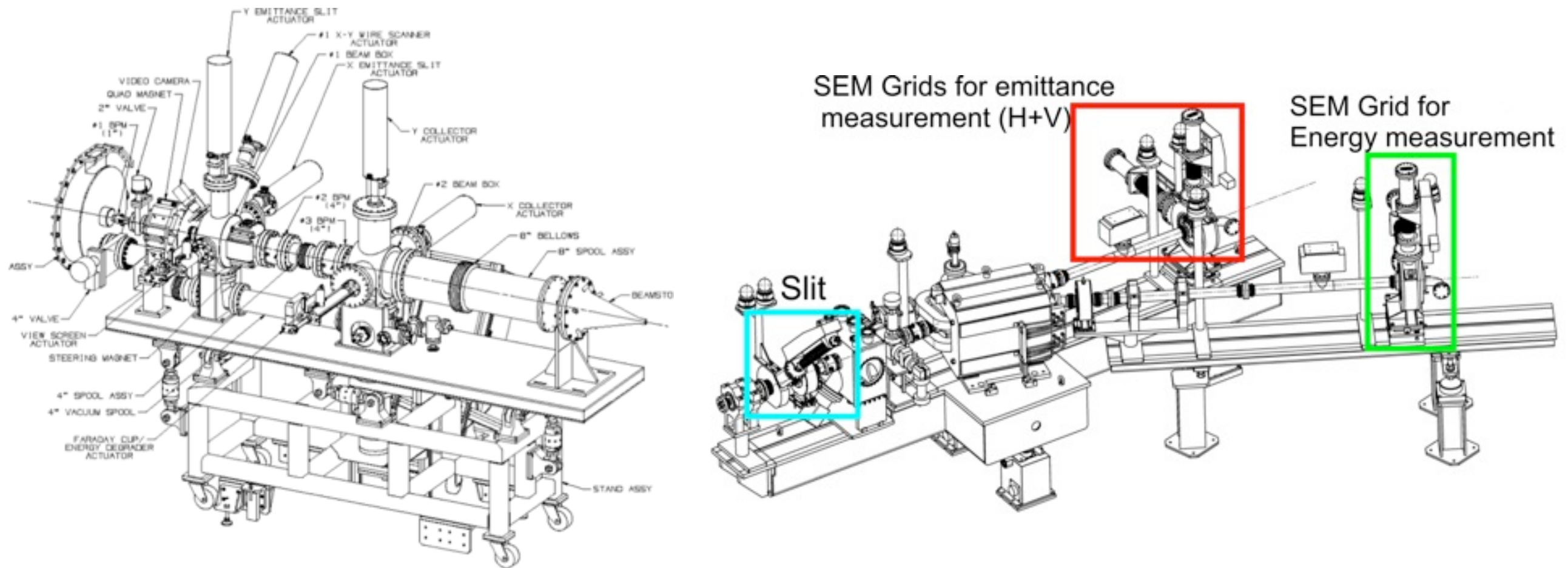


	BPM (position and TOF)
	Wire scanner
	BPM (chopping efficiency)
	Faraday cup (beam stopper)

**Proposal : make a permanent test line in the MEBT:**

A beam stopper is needed for dedicated studies of the MEBT

# Diagnostic test bench



A movable diagnostic test bench would be useful for:

- Beam optic studies
- Test and commission all Beam instrumentation
- Integration of special instruments for commissioning.



# Drift Tube Linac

Strong similarities to Linac4 at CERN. Preliminary beam dynamics calculations & EM design have been performed.

Recent decision to design the extended DTL for 50 mA with emphasis on high reliability.

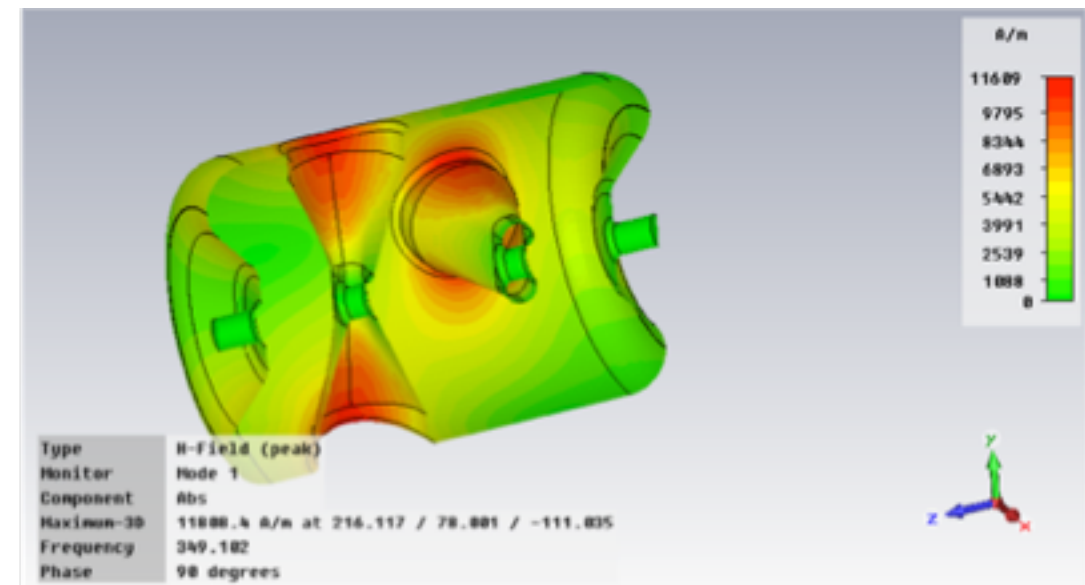
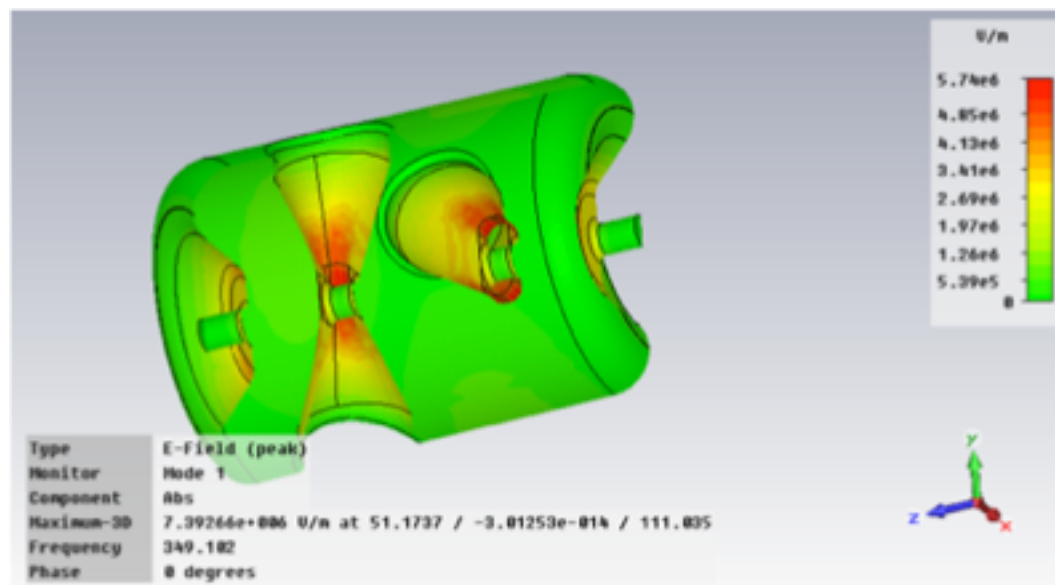
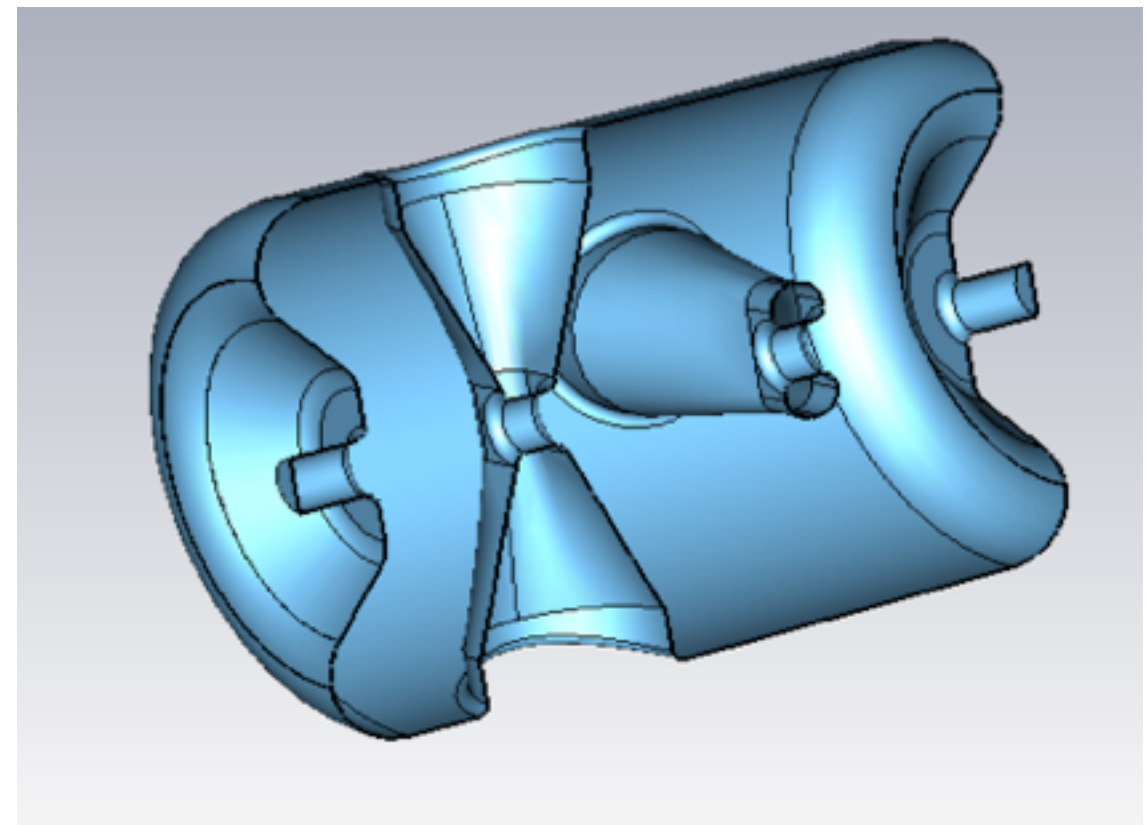
Linac technology will have advanced so much by the time that ESS will be upgraded that it is not motivated to build the front-end for more than 50 mA today.

It was also decided to defer the discussion about the RFQ design current to after the NC linac review in June.

The DTL-to-spoke cavity transition energy will be increased to about 80 MeV.

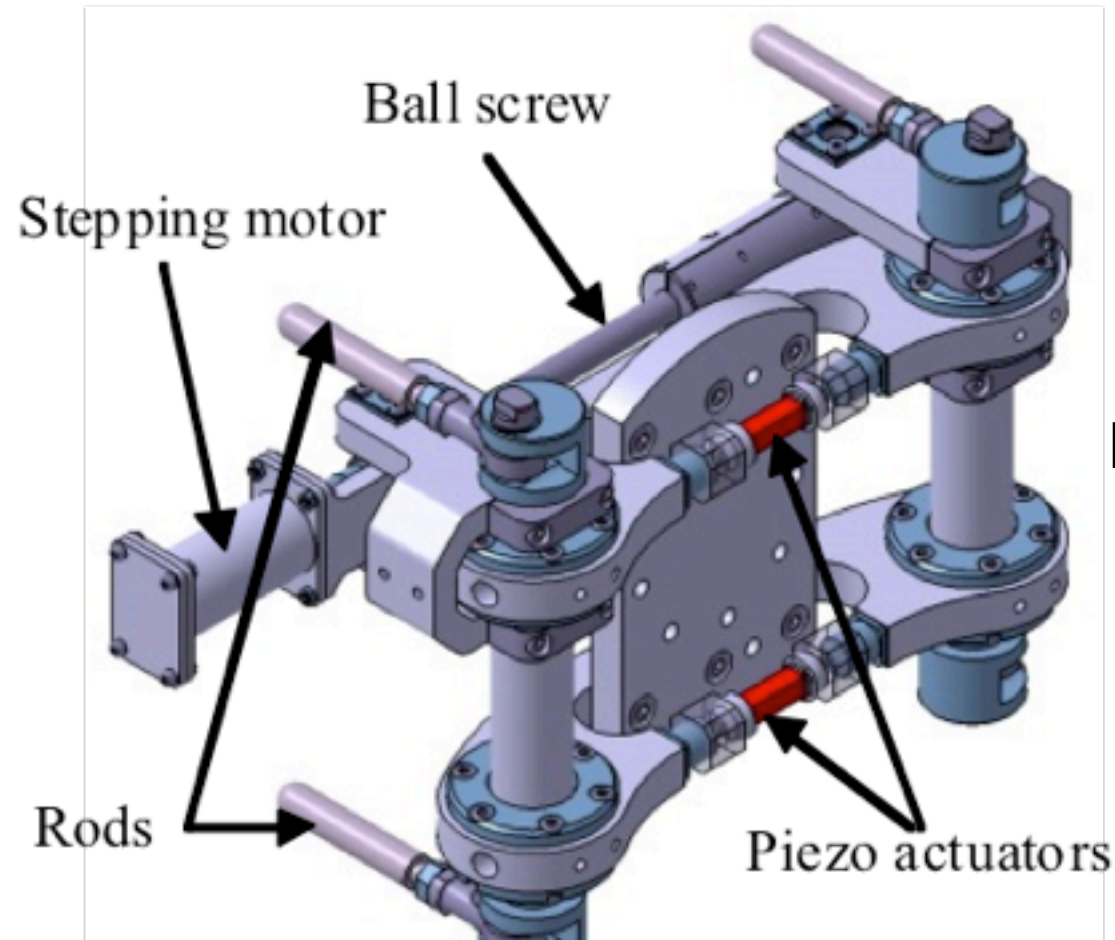
# Spoke resonators

F75: Overall aspect of the double spoke cavity.



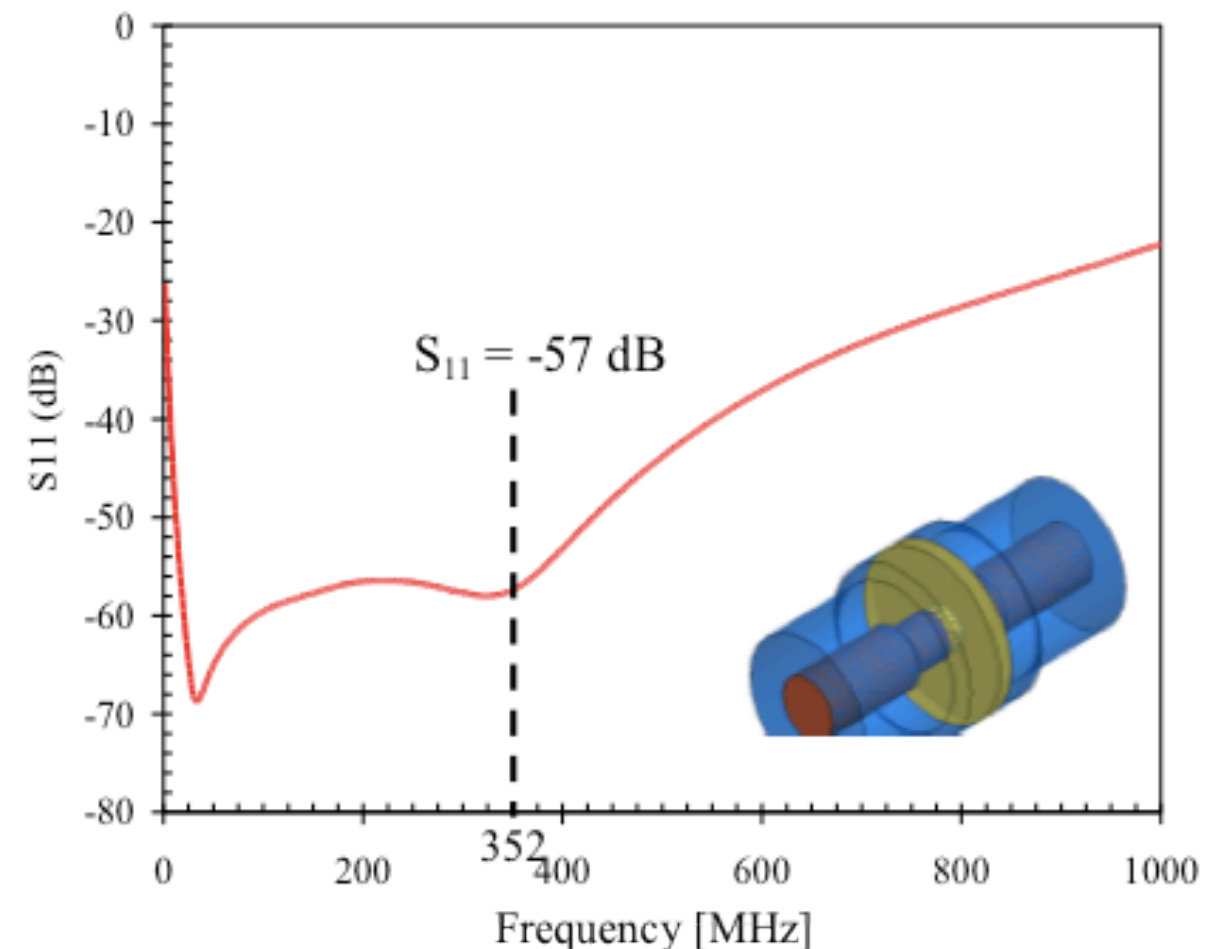
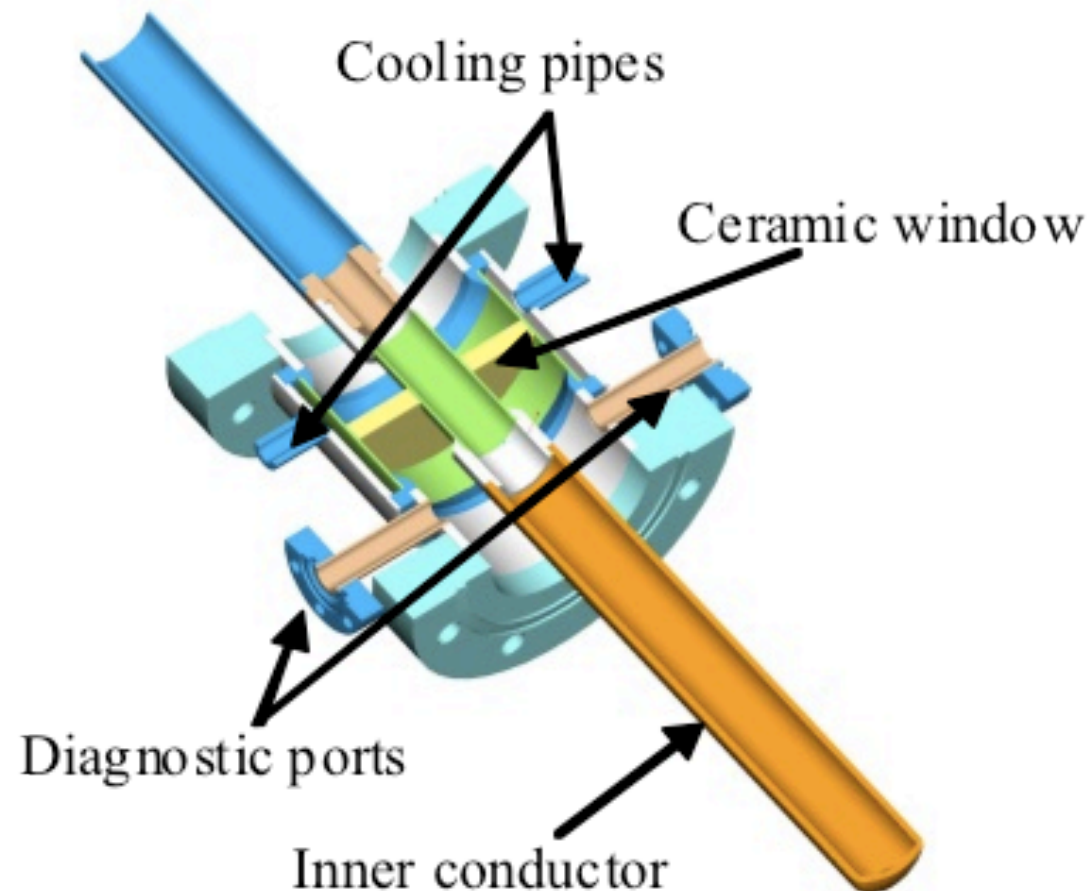
F76: Distribution of surface fields in the spoke cavity. Left: Electric. Right: Magnetic.

# 352 MHz leverage



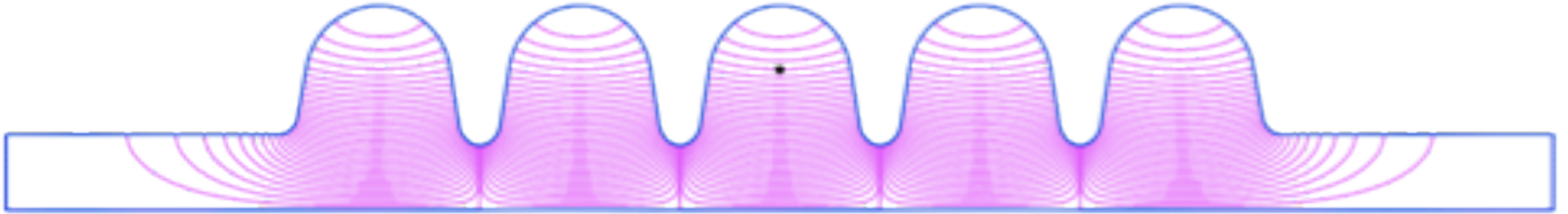
F79: Cold tuning system for spoke resonators.

F80: Conceptual design of a 352 MHz spoke power coupler of 56 mm diameter and computed return loss  $S_{11}$ .

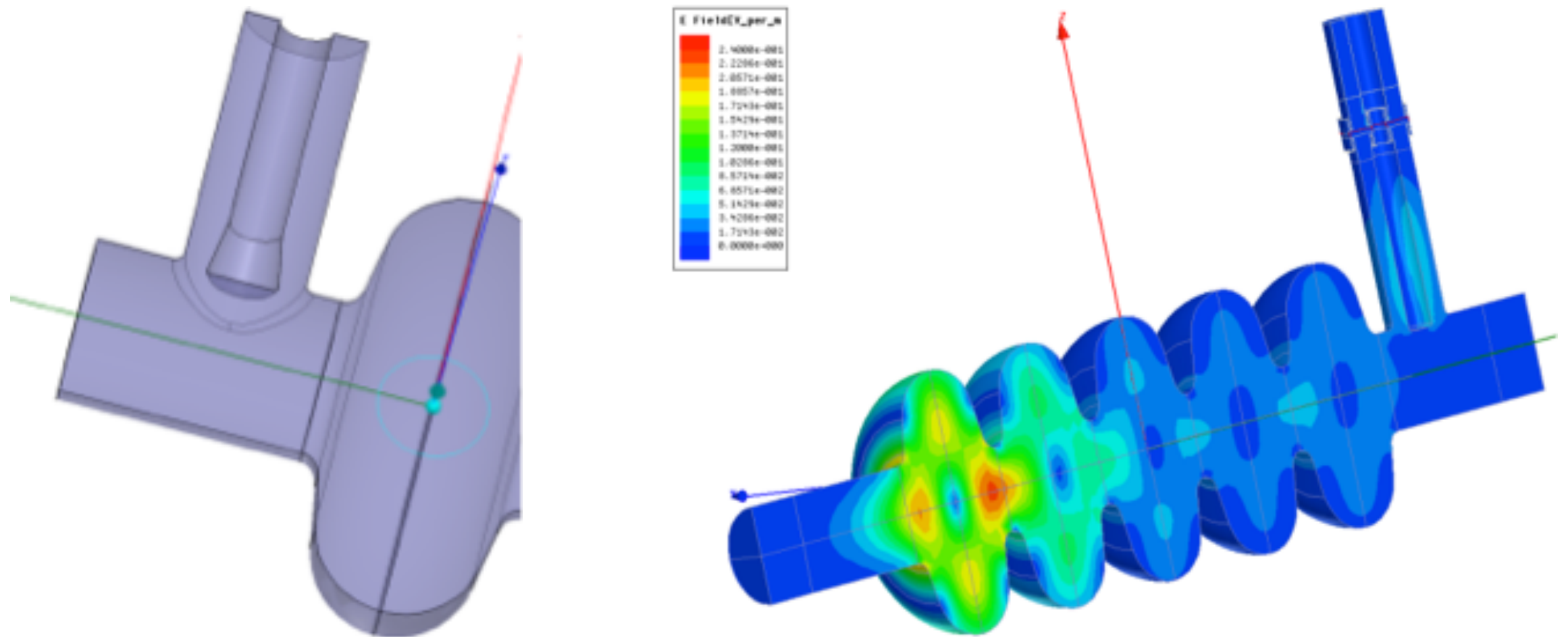




# Medium & high- $\beta$ ellipticals

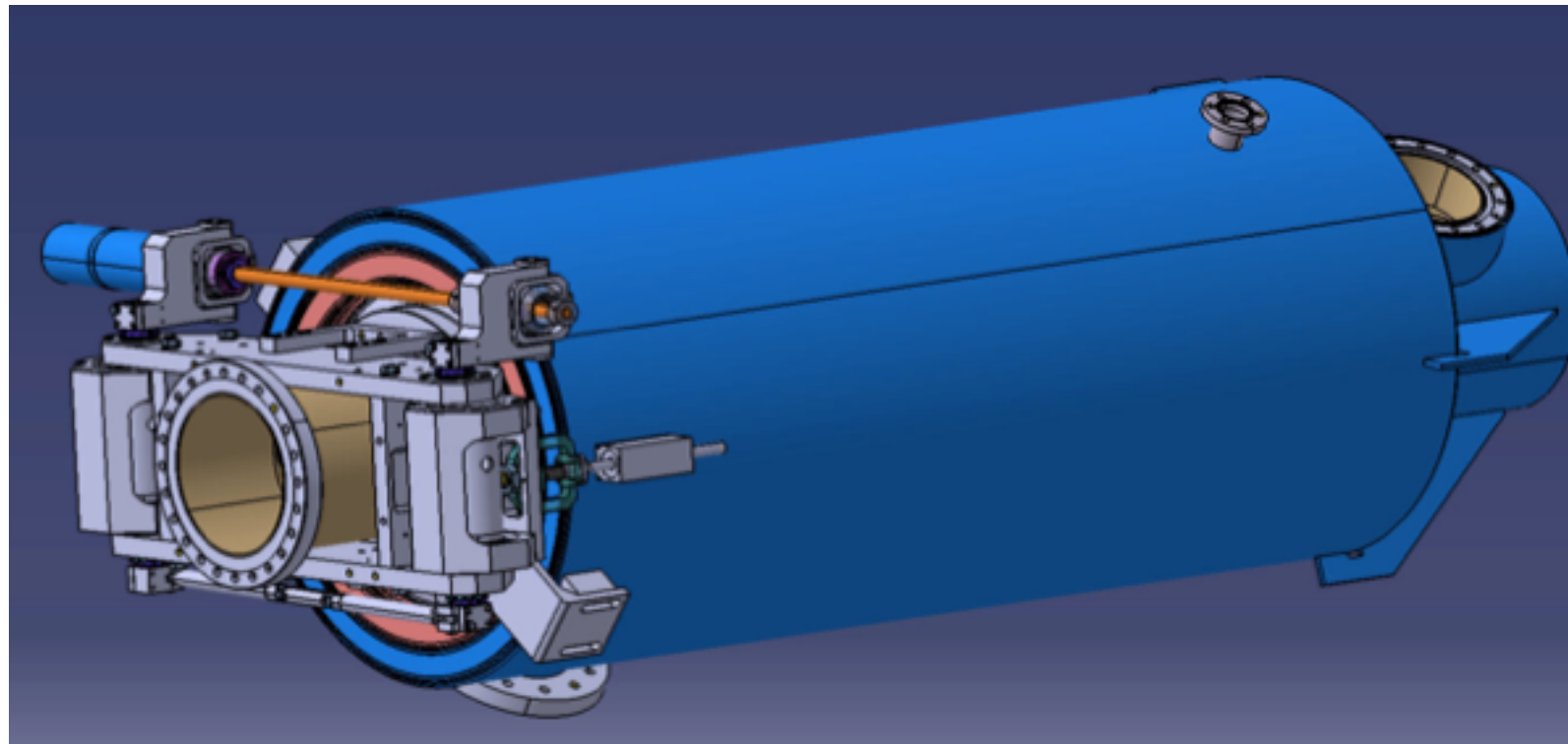


F81: Geometry of the prototype high beta ( $\beta = 0.86$ ) cavity.



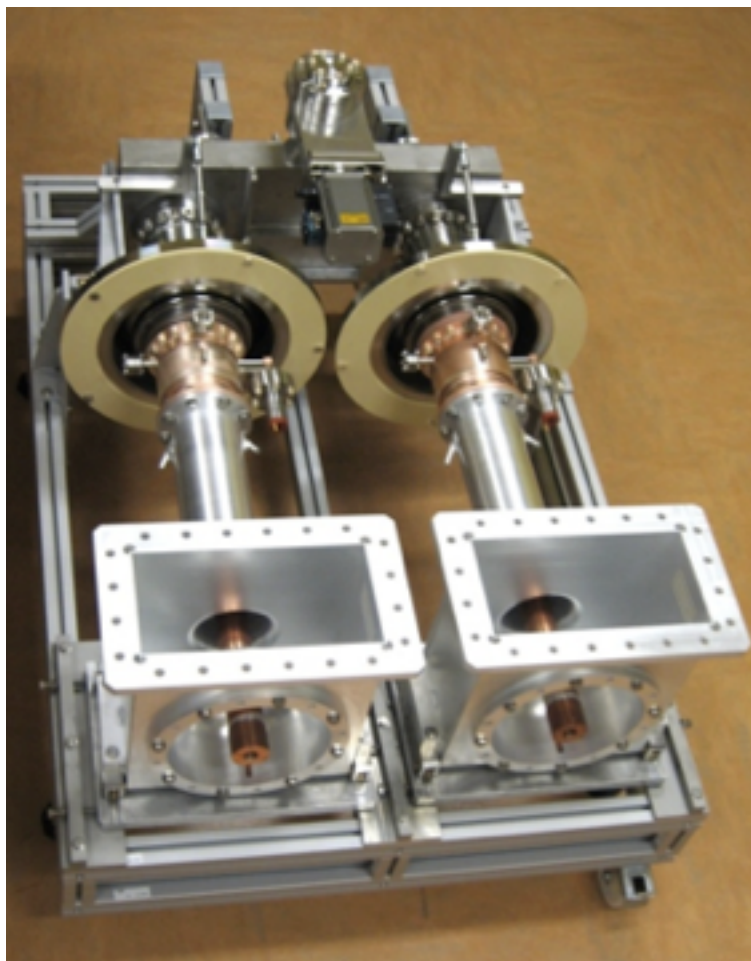
F83: Elliptical cavity geometry and higher order mode performance.

Left: Geometry of coupler-side end-group. Right: Lowest frequency TM monopole mode.

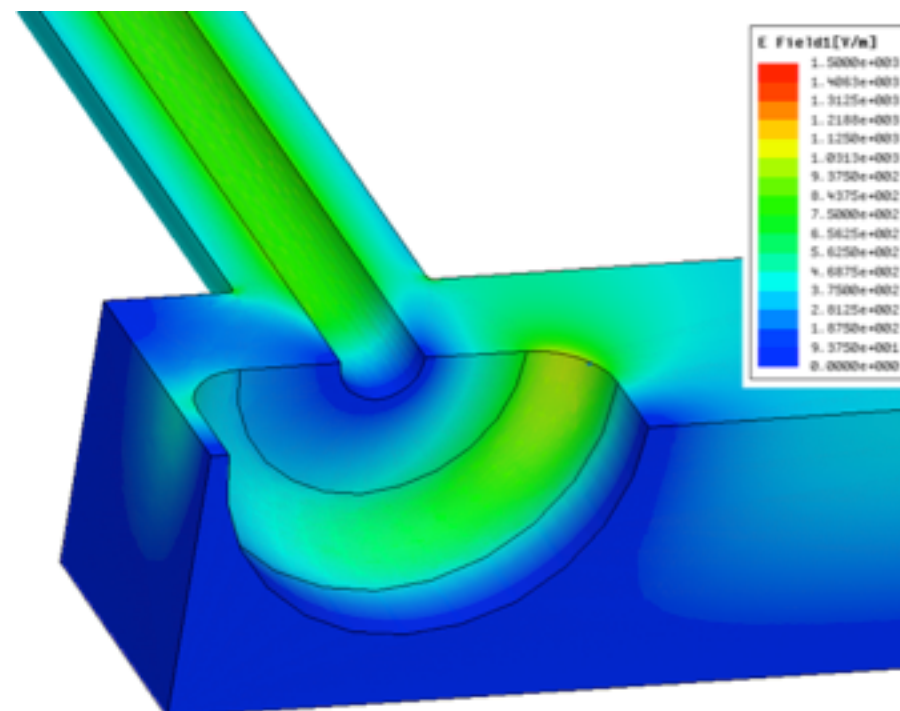


704 MHz  
leverage

F84: High beta elliptical cavity with a titanium helium vessel, and an integrated piezo tuner.

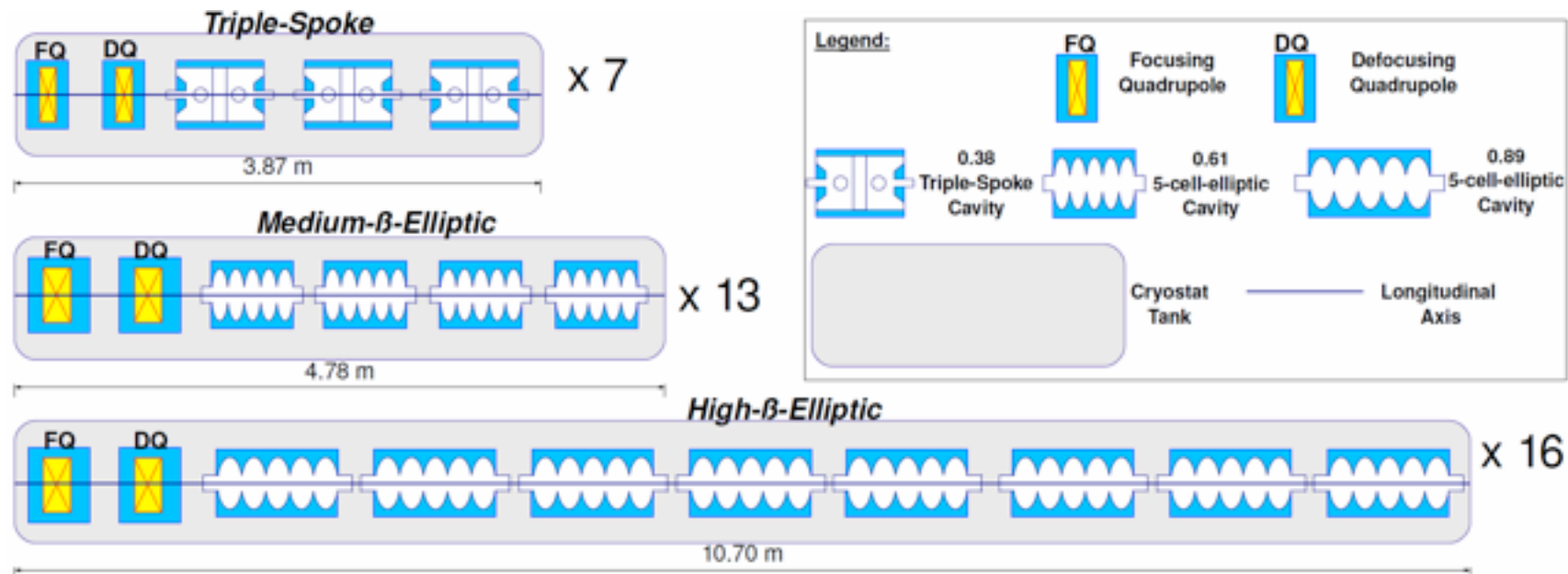


F85: Left: The CEA-Saclay 1 MW power coupler, with an outer diameter of 100 mm and an impedance of 50  $\Omega$ .



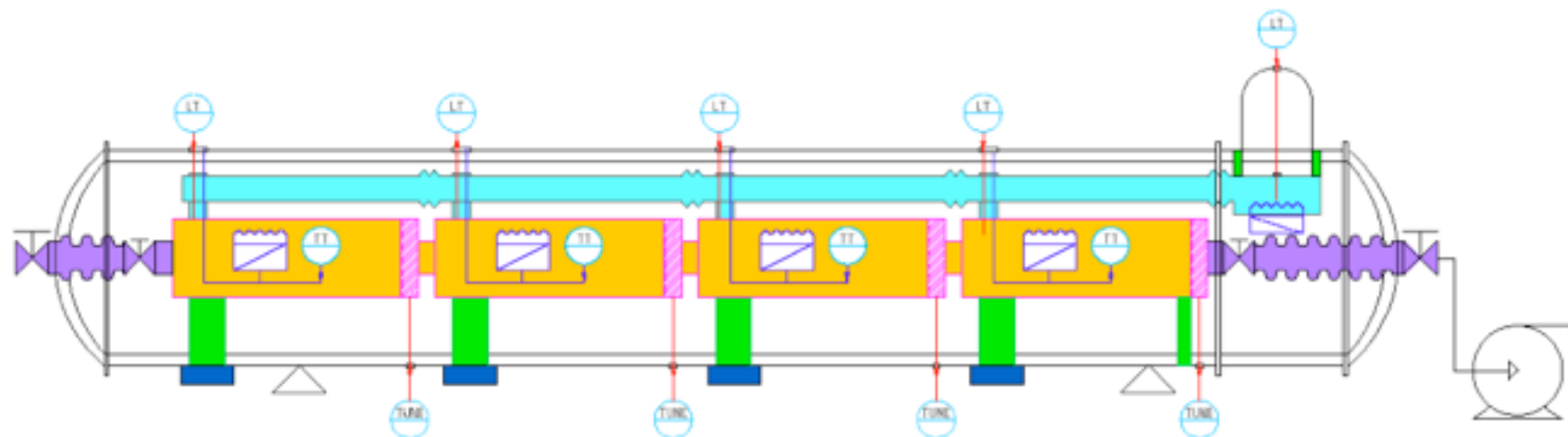
F86: Electric field distribution in the doorknob transition between rectangular & coaxial waveguides.

# Cryomodules - 2010



“2010 BASELINE”

continuous elliptical  
cryomodules (LEFT)

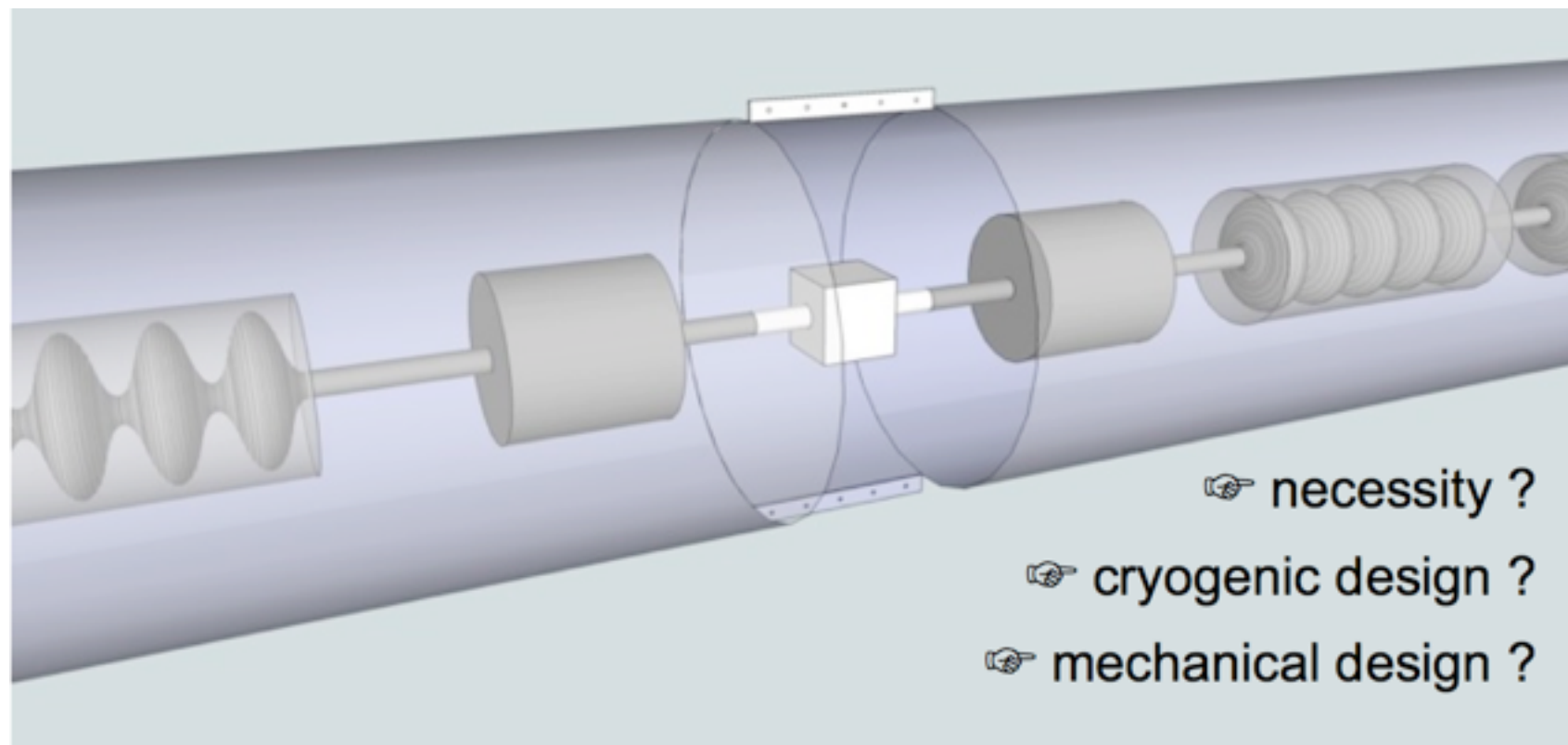


SPL/ESS

A “half” cryomodule  
is being built & will  
be tested at SM18 in  
collaboration with  
CERN.

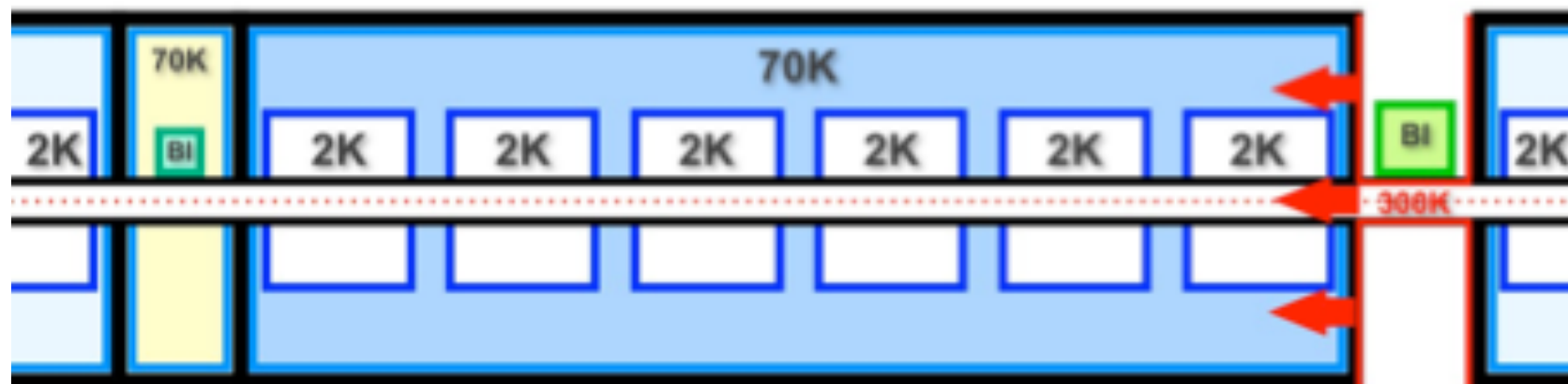


# Cryomodules - 2011



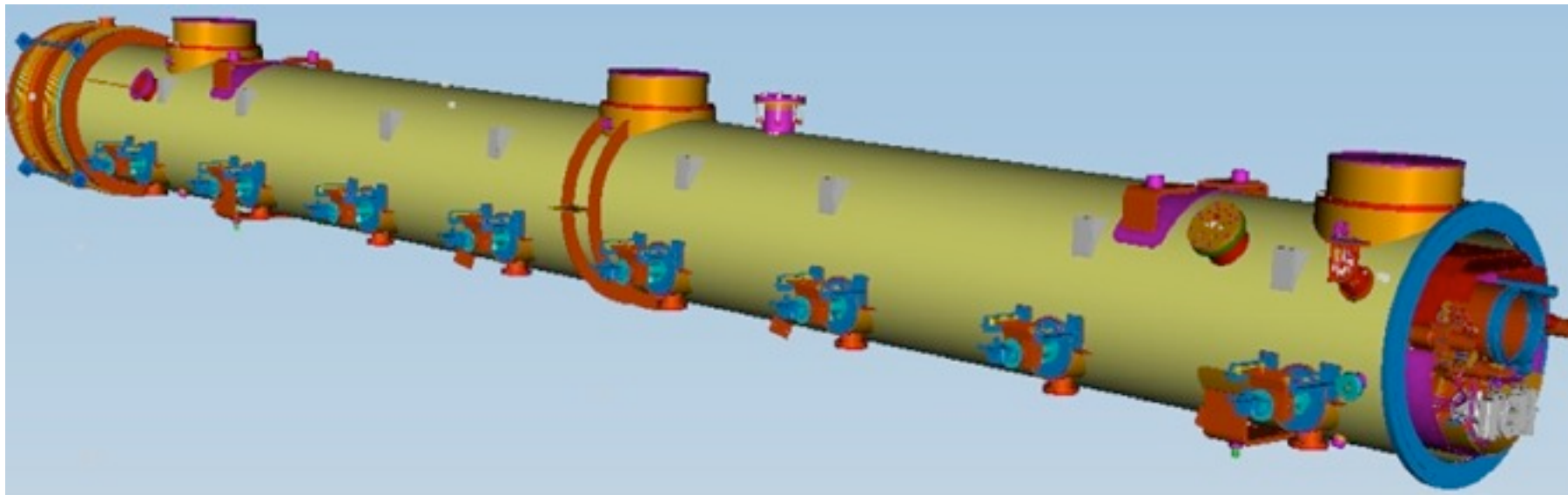
“2011 HYBRID”  
layout is used in  
HS\_2011\_11\_23

A ~70K sleeve  
encloses (most cold)  
interconnects,  
reducing heat load.

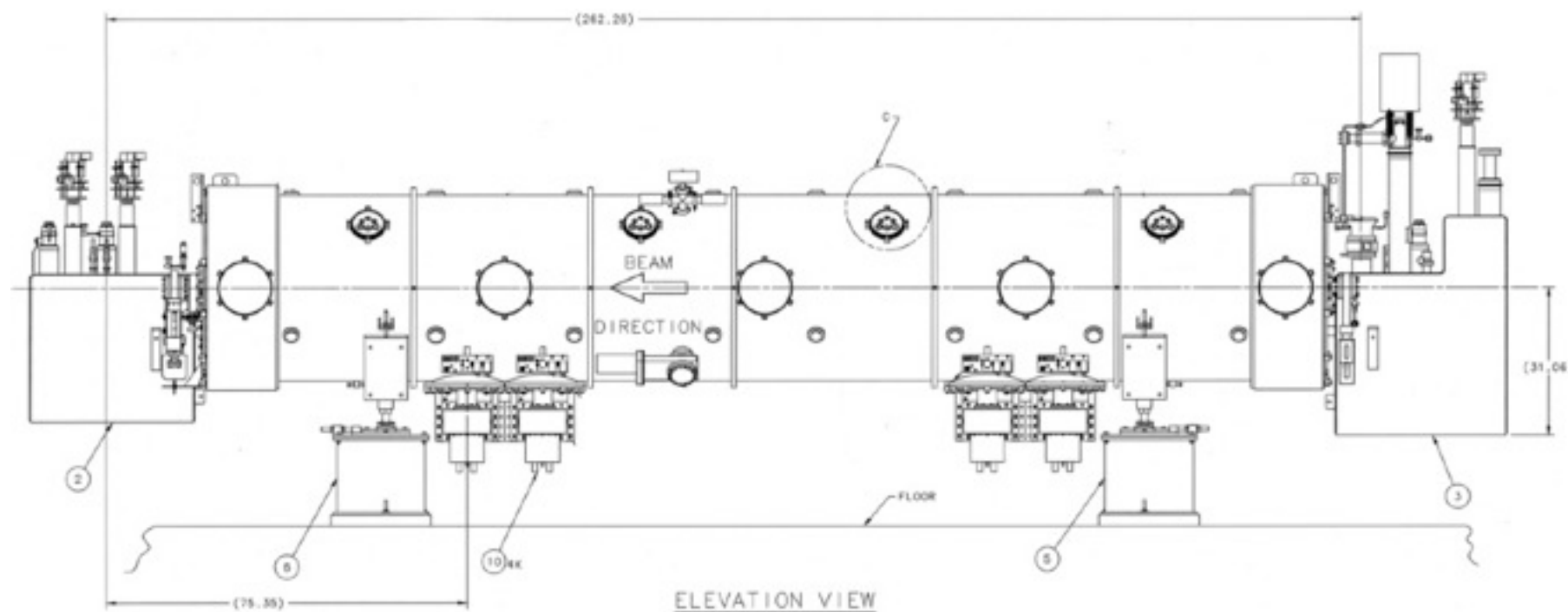


Some interconnects  
may be left warm,  
e.g. to simplify beam  
instrumentation.

# Continuous, segmented, or .....

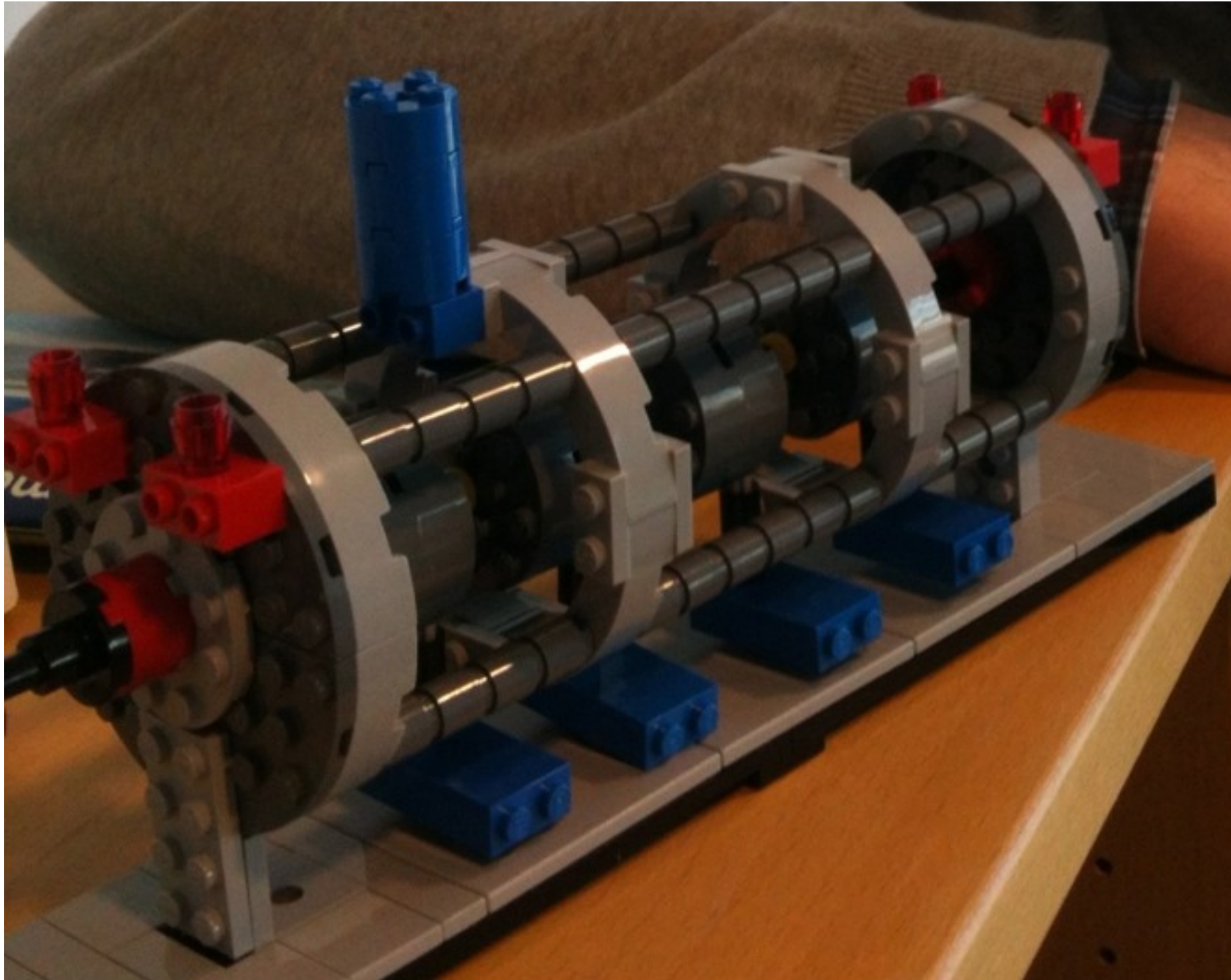


F90: A continuous cryomodule with internal cryogenic lines - XFEL.



F89: Typical segmented cryomodule, from the SNS.

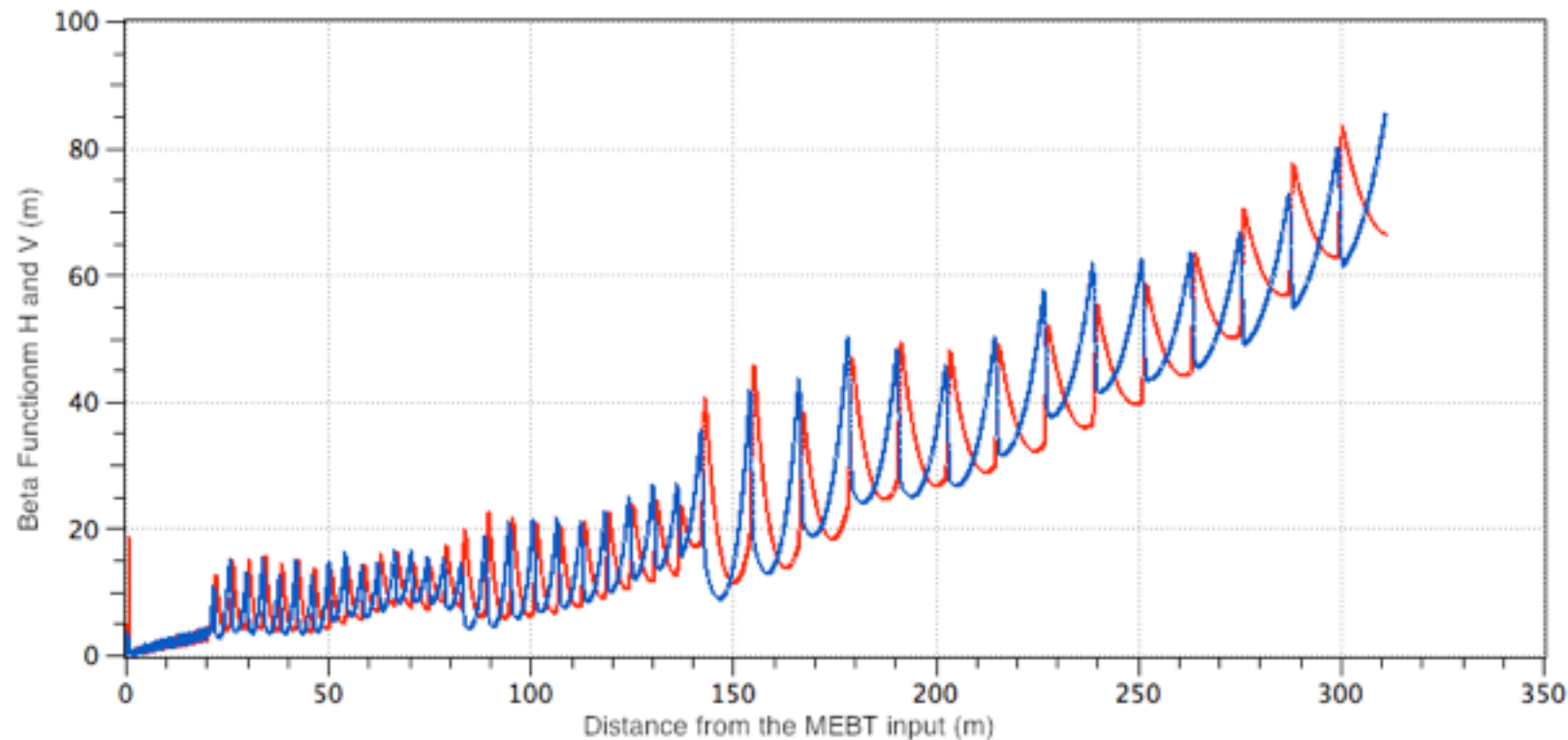
# ... LEGO?



Careful thought and a sophisticated design process indicates that the 2012 releases of the ESS lattice (May & Oct) will use segmented CMs

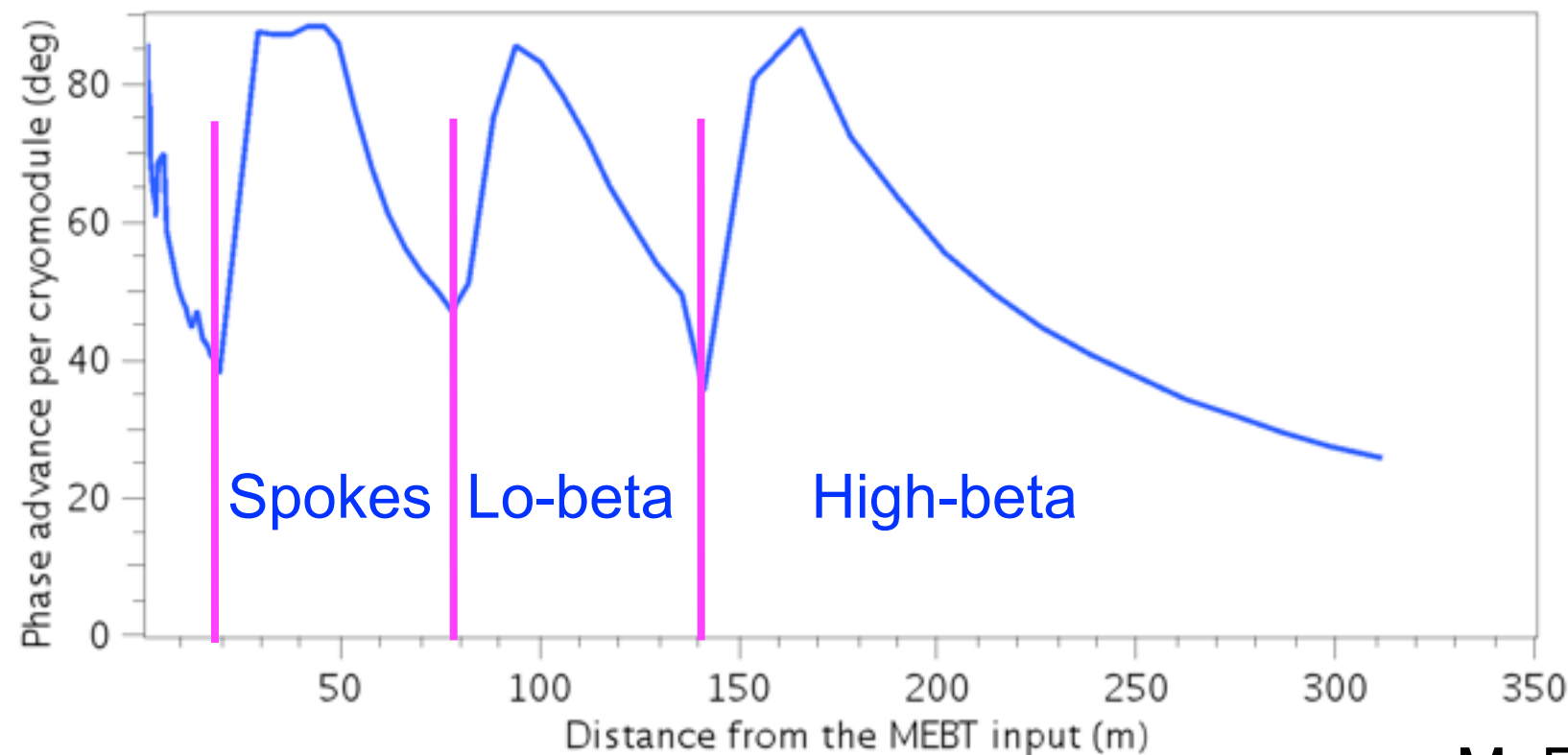


# SRF linac optics



Transverse beta functions  
Increase smoothly

- weakening doublets
- ~constant beam size
- little emittance growth



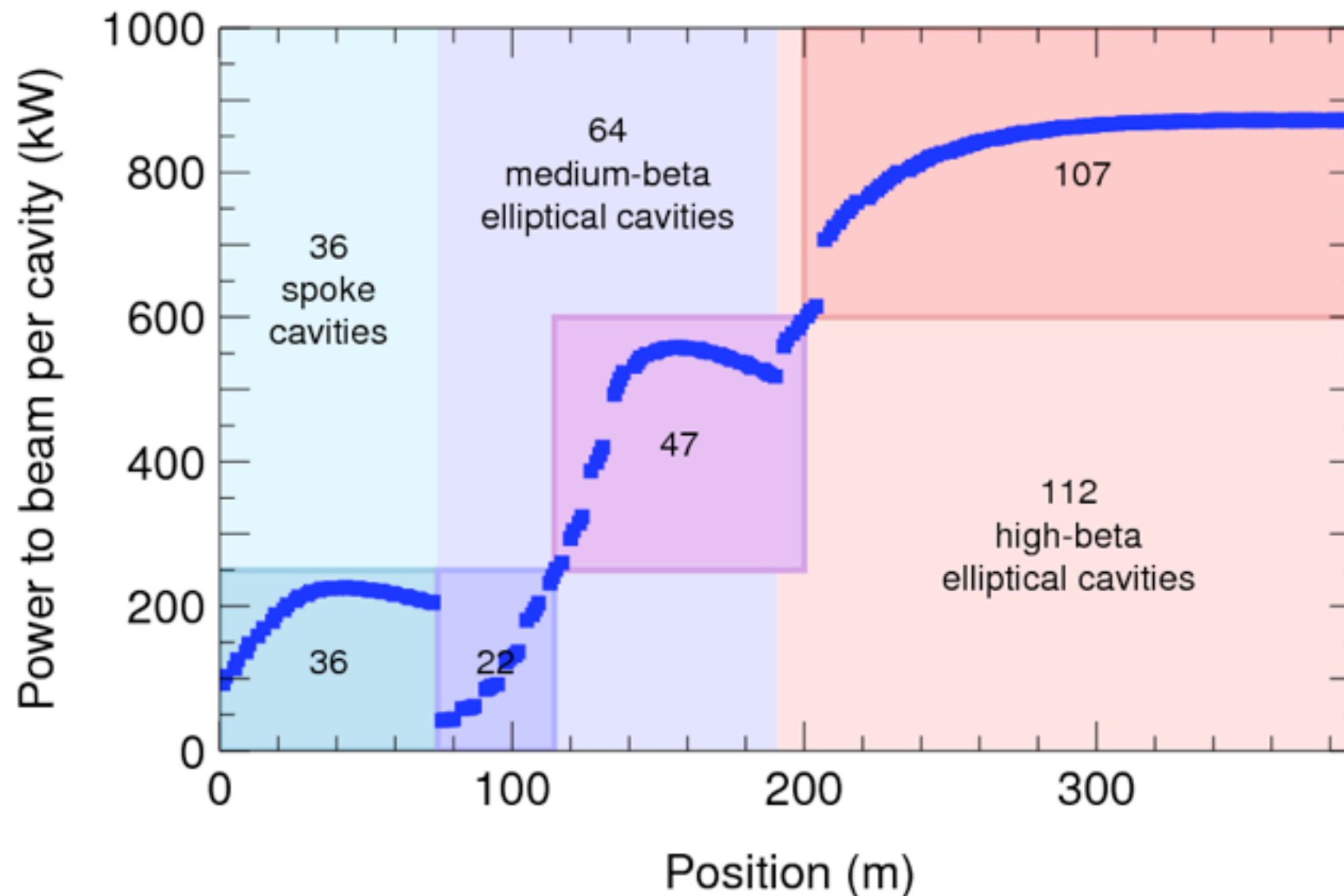
Longitudinal optics

Represented by phase  
advance rate

- matched transitions
- one klystron per cavity

M. Eshraqi, H. Danared, K. Rathsmann

F59: The power gained by a 50 mA beam in each cavity in the HS 2011 11 23 lattice [82]. Background colours indicate different cavity types and RF sources.

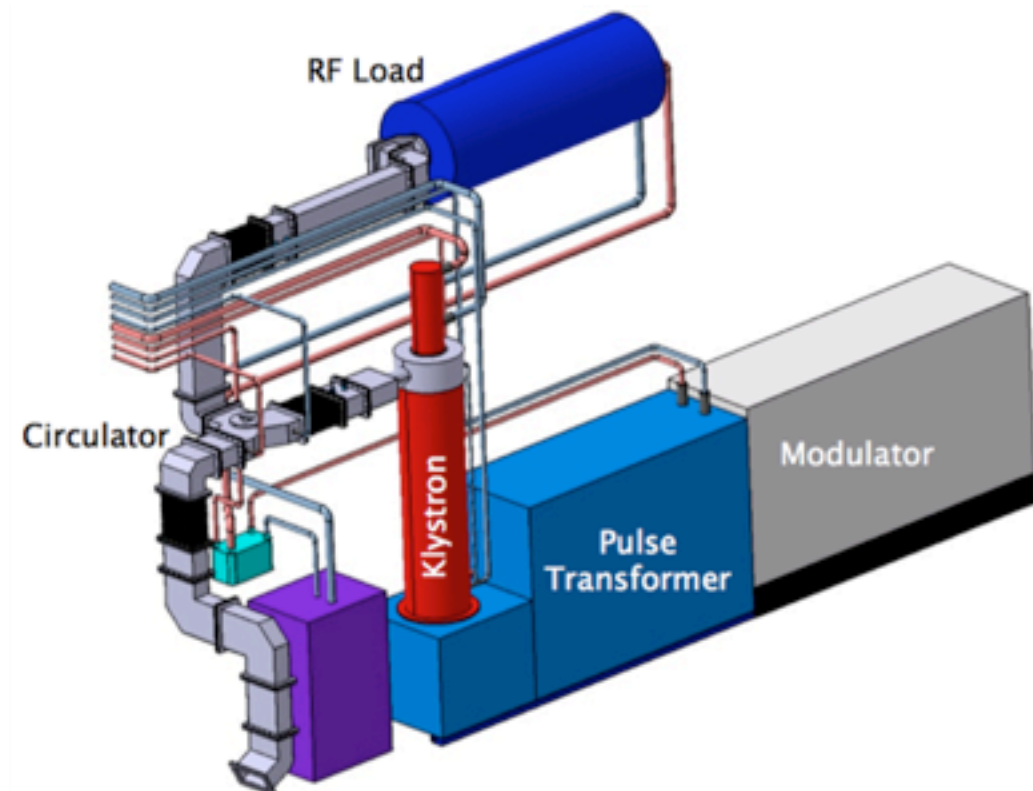
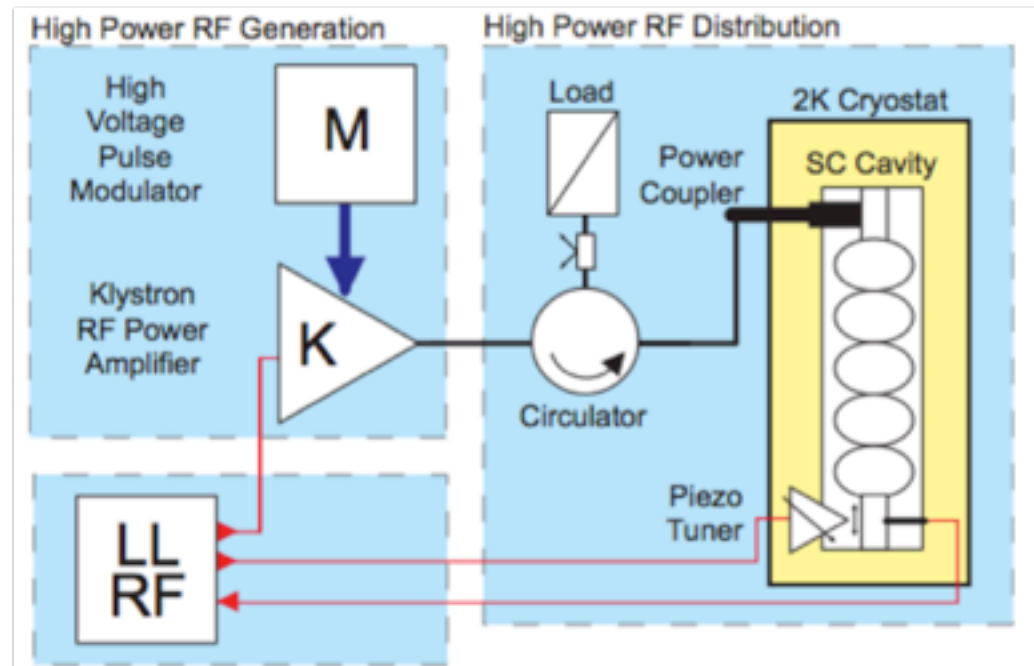


Extrapolate these idealized optics to the real world:

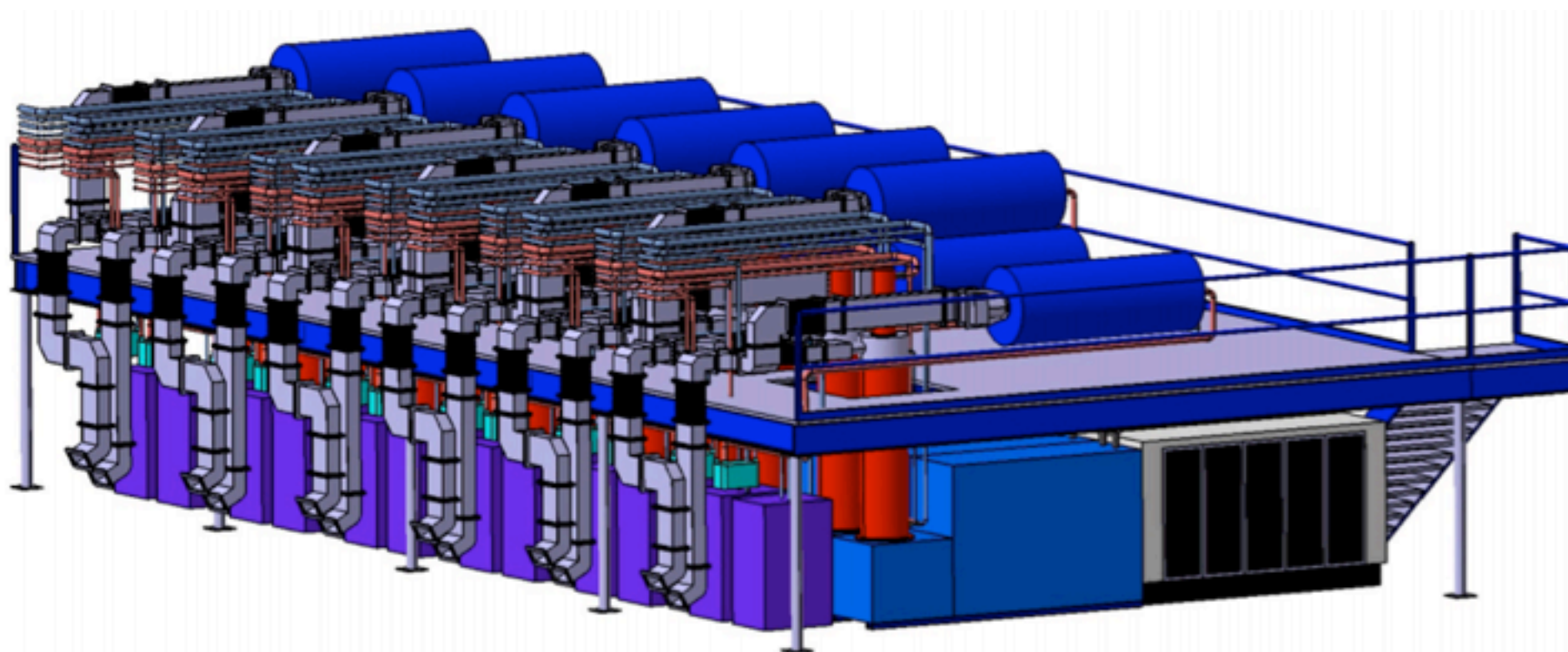
- SNS experience with a **broad range of as-built cavity gradients**
- ILC planning for a **+/-20% range of gradients**

Quality assurance, production testing, sorting, re-tuning, simulating?

# Klystron gallery



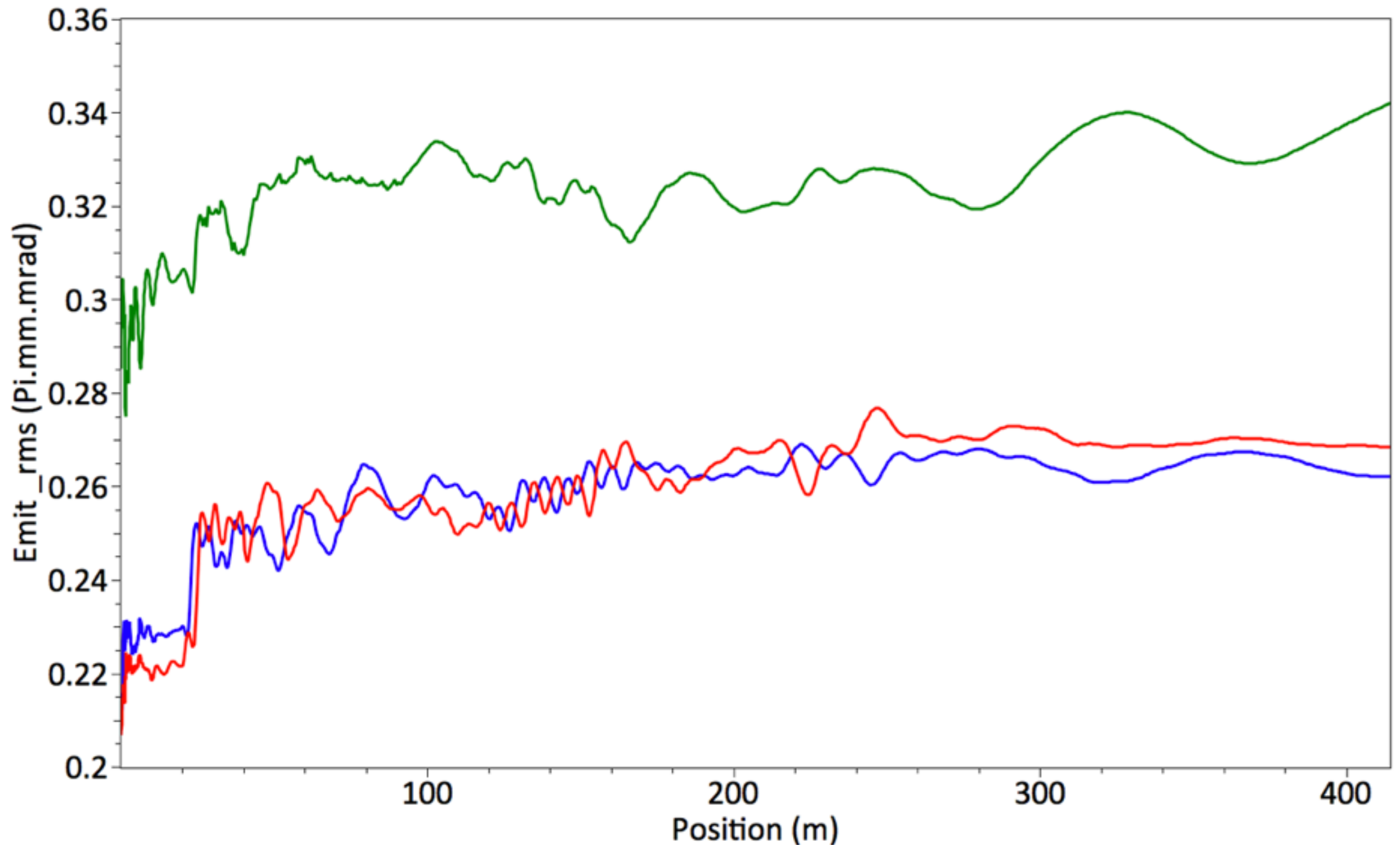
F96: System block diagram of a klystron RF system, with one cavity per power source.



F99: Possible layout of a section of the equipment gallery, with one klystron per modulator.

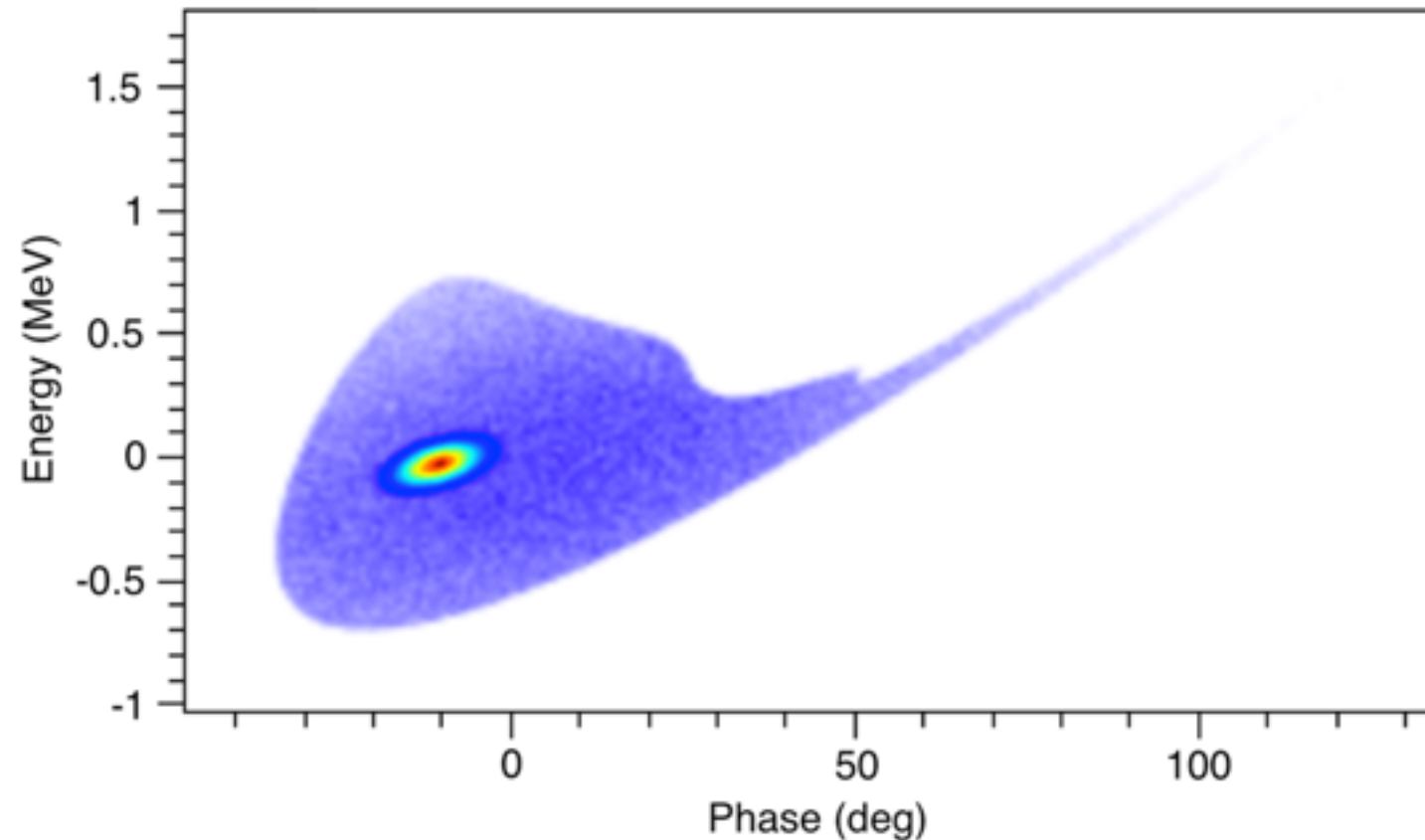


# Beam dynamics - emittance growth

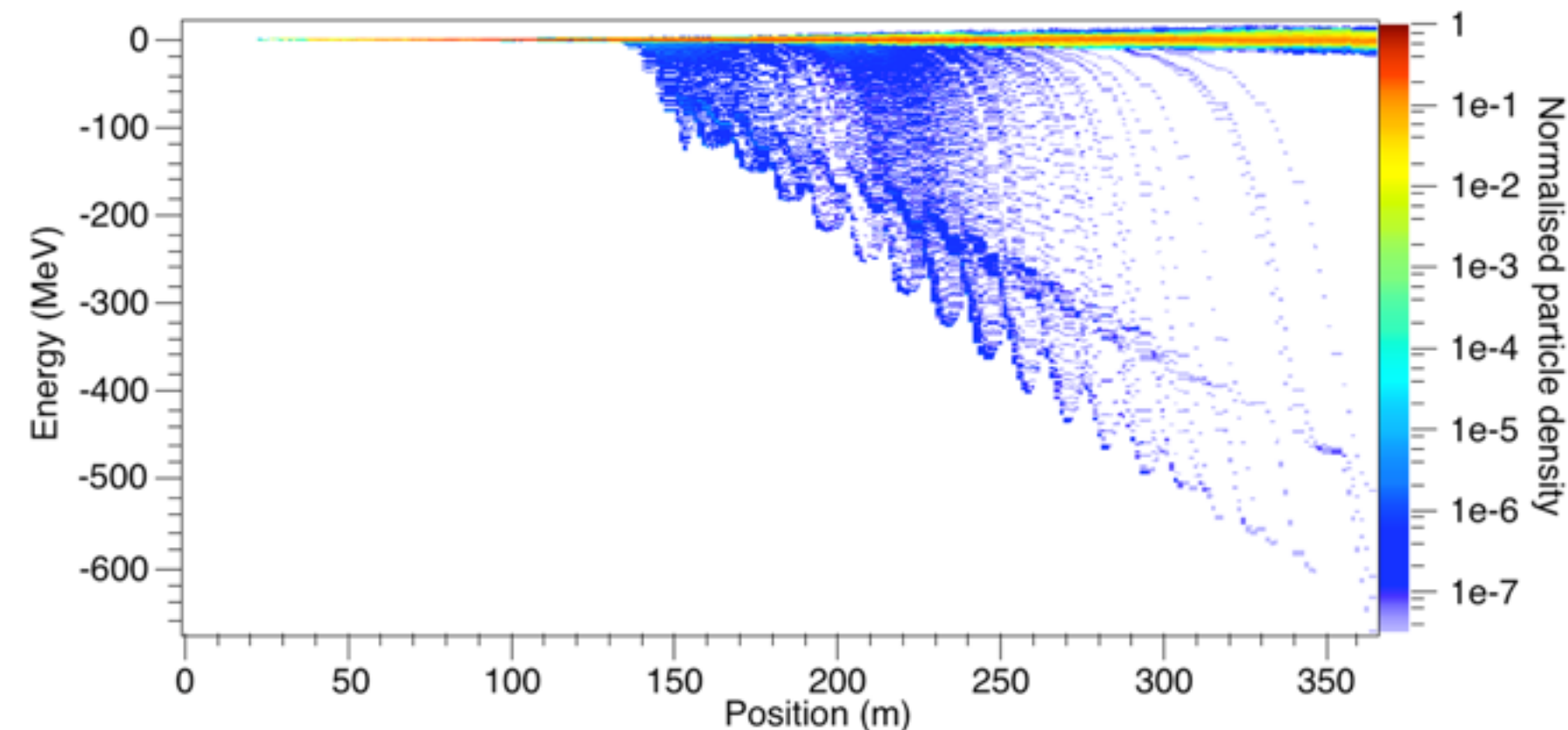


F64: Horizontal (red), vertical (blue) and longitudinal (green) RMS emittance in the HS\_2011\_11\_23 linac, from the entrance to the RFQ to the last elliptical cavity.

# Acceptance & transverse beam loss



F65: Acceptance (blue background) and matched beam (multi-coloured ellipse) at the entrance to the HS\_2011\_06\_22 superconducting linac.



F67: Particles falling out of the RF bucket in the superconducting linac & getting lost in a case of **unrealistically** large RF amplitude ripple and phase jitter of 2% and 2 degrees.

# Beam losses

Radio-activation is unacceptable from losses larger than about **1 W/m**.

**Intra-beam stripping** is the dominant source (?) of beam losses in H-linacs like the SNS (**0.2 W/m**) - but not in the H<sup>+</sup> ESS !

Other potential beam loss sources:

1. **Space charge resonances**
2. **Transverse overfocusing**
3. **Uncollimated low energy beam halo**

**Confidently predicting the relative importance of loss mechanisms is a fundamental challenge to our ability to design multi-MW proton linacs.**

Resolve by 1) simulation & theory, 2) **experiment** (eg, SNS) .....



## Higher Order Modes

- There is risk in **NOT** damping, & also **IN** damping HOMs
- HOM couplers will be installed if ongoing studies indicate the need
- Could be instrumented to measure transverse displacements

## Field Emission & Multipacting

- SNS experience indicates that FE & MP may limit cavity performance
- Excessive power into HOM electronics, via thermal detuning?
- A simulation campaign has been launched

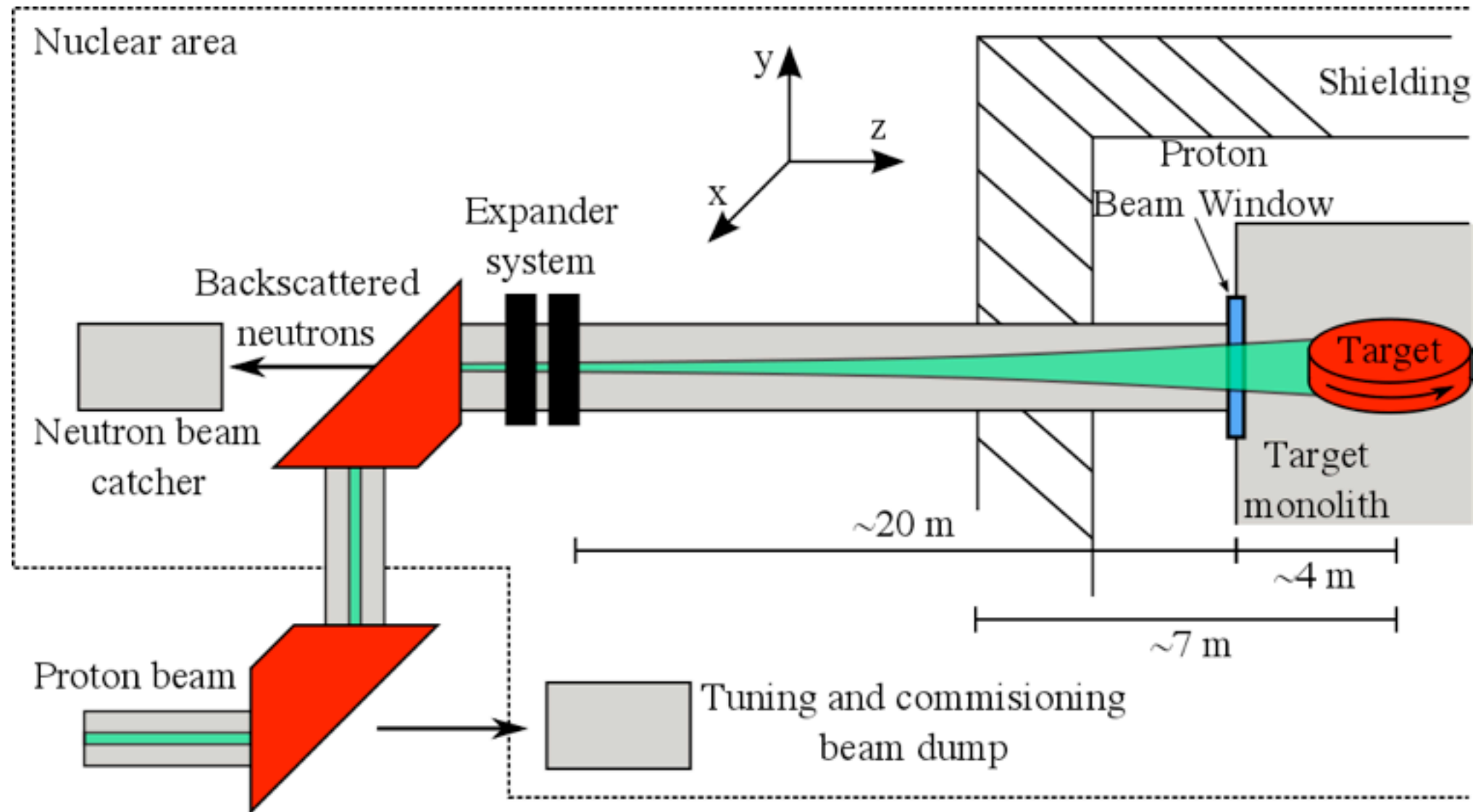
## Low Level RF

- Protons: semi-relativistic speeds cause phase & amplitude errors to accumulate along the linac
- Investigations (eg of modulator ripple & droop) are in progress

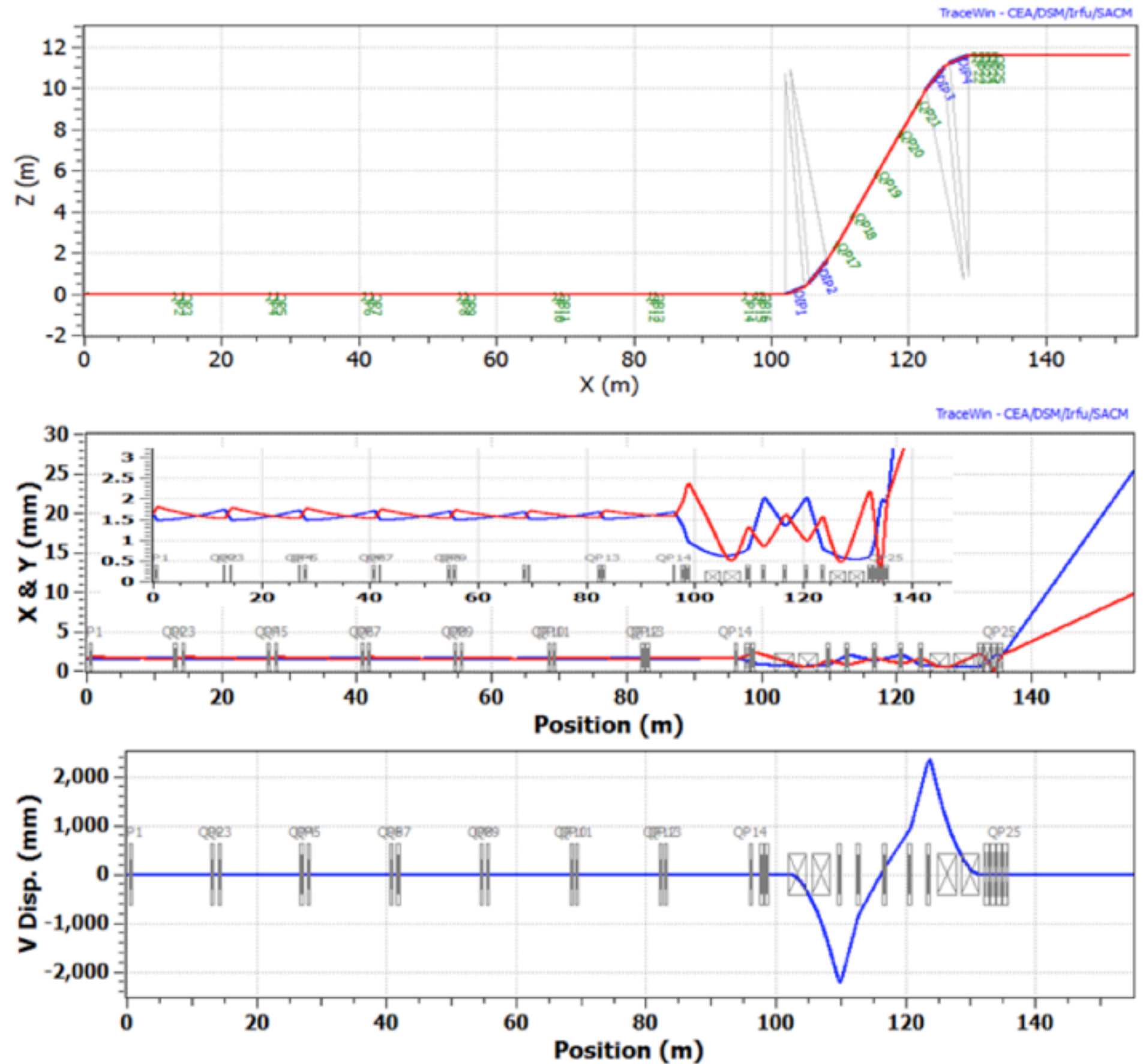
# Target-to-accelerator

## Accelerator-to-Target

- Rise from -10 to +1.6 m
- Tune-Up Dump
- Beam windows
- Distributed systems
- Beam diagnostics
- Protection systems



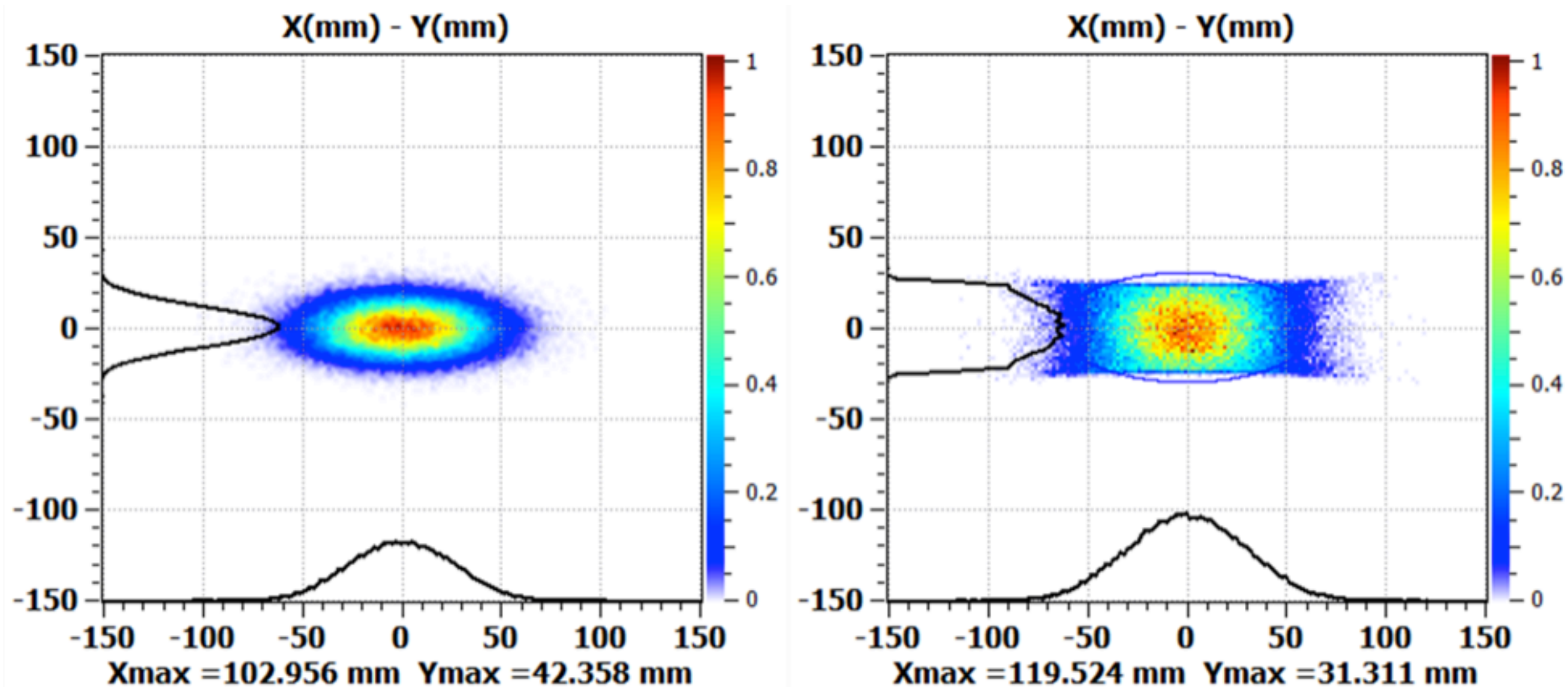
# HEBT



F93: Top: The layout of the HEBT. Middle: RMS beam sizes – H (blue) & V (red). Bottom: Vertical dispersion function. Beam sizes & dispersion are based on envelope calculations.



# Beam spreading optics



F94: The beam foot print obtained at the target from multi-particle simulations of 105 particles. Left: By quadrupole expansion. Right: By octupole expansion. The colour scale (representing particle density) in each case is scaled to the maximum value.

# Summary

# ESSon the ADS roadmap

**Finding #5:** “The missions for Accelerator Driven Sub-critical (ADS) technology lend themselves to a technology development, demonstration & deployment **strategy** in which **successively complex missions** build upon technical developments of the preceding mission.”  
U.S. Dept. of Energy White Paper (2010).

Table 2: Accelerator Requirements for three reference ADS Designs

	Transmutation Demonstration (MYRRHA [5])	Industrial Scale Facility driving single subcritical core (EFIT [10])	Industrial Scale Facility driving multiple subcritical cores (ATW [11])
Beam Energy [GeV]	0.6	0.8	1.0
Beam Power [MW]	1.5	16	45
Beam current [mA]	2.5	20	45
Uncontrolled Beamloss	< 1 W/m	< 1 W/m	< 1 W/m
Fractional beamloss at full energy (ppm/m)	< 0.7	< 0.06	< 0.02

ESS [**\*\*50** mA in **2.9** ms pulses at **14** Hz]



# Summary

1. The European Spallation Source will be built in Lund.
2. “Accelerator Design Update” phase is starting to wind up, with the Technical Design Report in Jan 2013.
3. Then on to prototyping (P2B), site preparation, construction, installation, commissioning & operations.
4. UK involvement - who has what “unfair competitive advantage” for P2B?
5. RAL FETS: 324 MHz. Saclay FETS: 352 MHz.
6. Flexibility = Upgradeability + ?