ESS linac beam instrumentation and its challenges

Benjamin Cheymol

European Spallation Source

Uppsala U.
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Outline

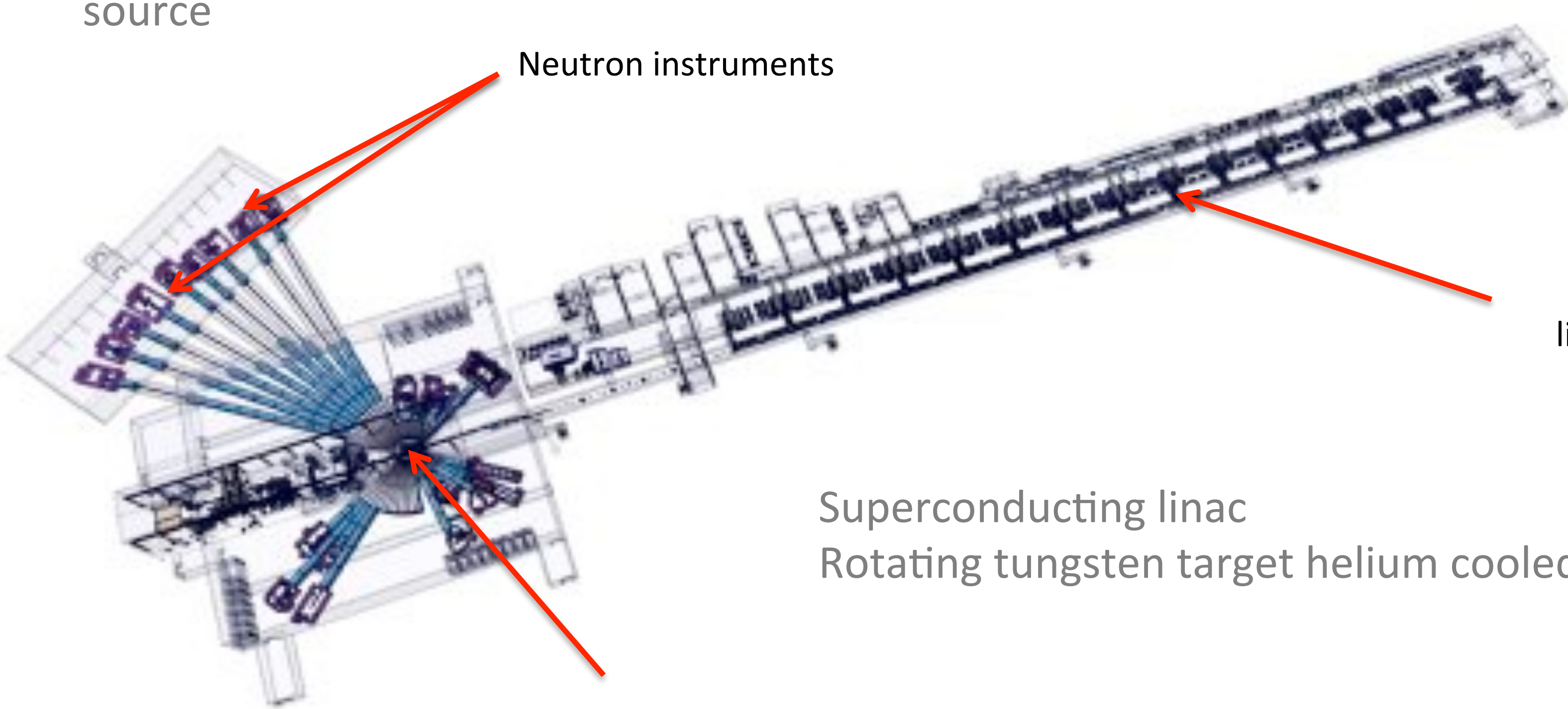
- Introduction
- Linac Beam diagnostic
  - Beam loss detection
  - General diagnostic suit for ESS
- Potential collaboration with Uppsala U.

European Spallation Source

EUROPEAN SPALLATION SOURCE

An European multi-disiplinary research centre based on the world's most powerful neutron source

Hosted by Sweden (source facility) and Danemark (data management facility)

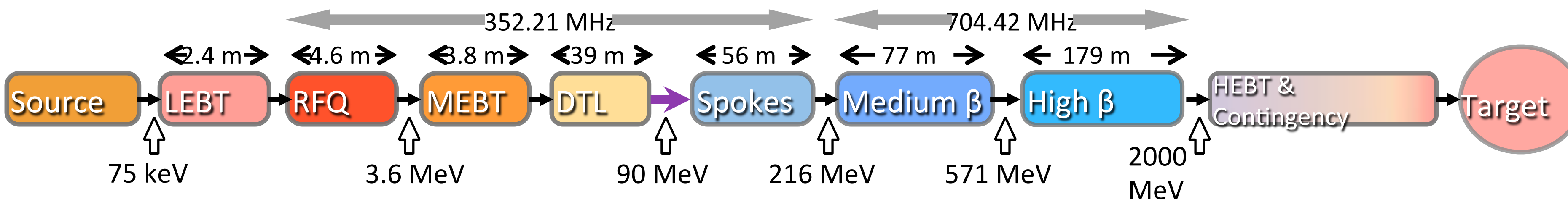


Superconducting linac
Rotating tungsten target helium cooled

Accelerator Layout Nov 22, 2012

ESS today

ESS Accelerator



Key parameters:

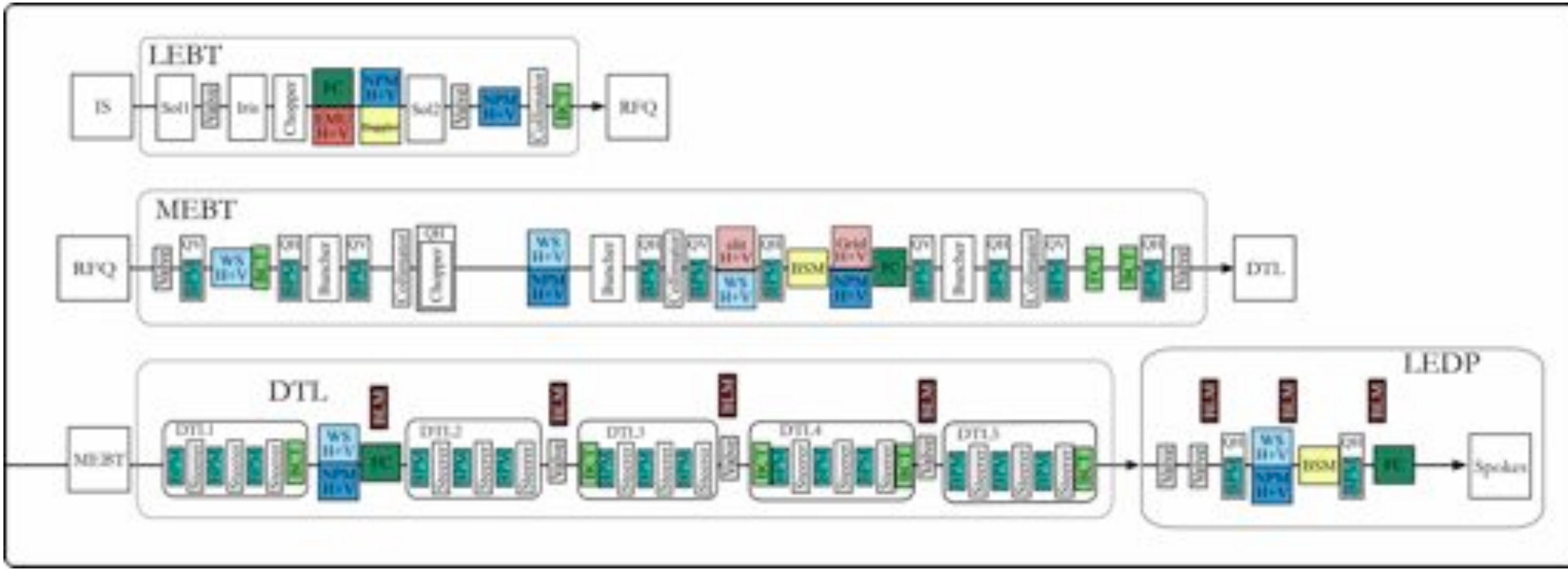
- 2.86 ms pulses
- 2 GeV
- 62.5 mA peak
- 14 Hz
- Protons
- Low losses

Beam parameters:

- Peak beam power @ 2GeV=> 125 MW
- Average beam sizes≈ 2mm (1 rms)
- Bunch length=> from ≈ 100 ps (MEBT) to 3 ps (High β)
- High flux => $1.5.10^{16}$ $protons.s^{-1}$
- Bunch frequency => 352,2 MHz (2.86 ns)
- Particle per bunch => ≈ 10^9 protons

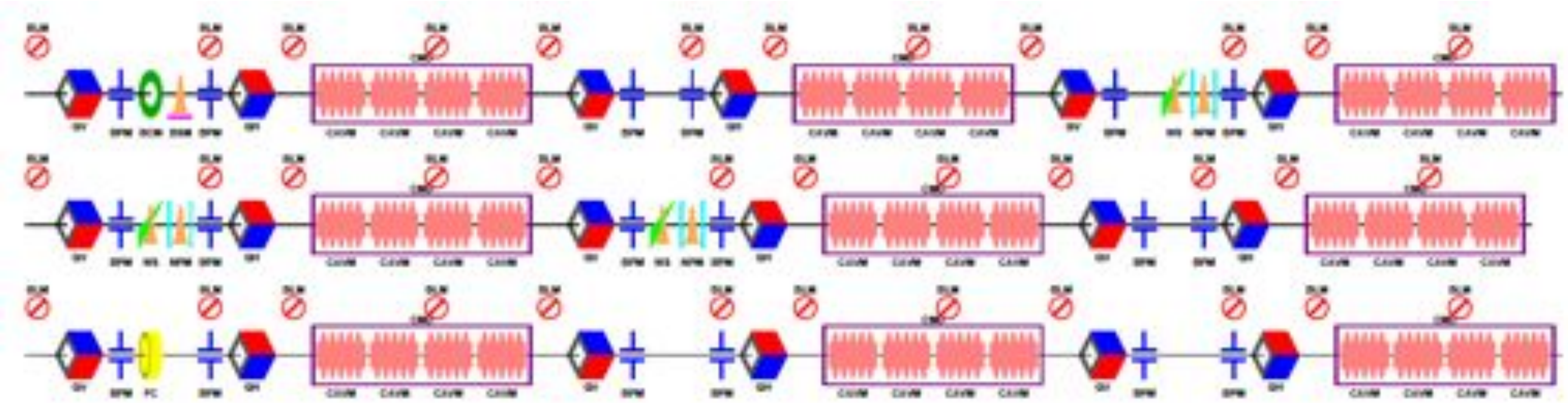
High power density => interceptive devices only inserted at low duty cycle
Space charge dominated beam => space restriction for instrumentation

BI layout example (warm linac)



- Measure 6-D phase-space of the proton beam at the exit of the IS and of the RFQ
- Current along pulse: Beam Current Monitor (**BCM**)
- Emittance Measurement Unit (**EMU**): Allison scanner and slit and grid
- Beam position: Beam Position Monitor (**BPM**)
- Bunch Longitudinal profile: Bunch Shape Monitor (**BSM**)
- Beam losses: Beam Loss Monitor (**BLM**)
- Beam transverse profiles: Wire Scanner (**WS**), and Non invasive Profile Monitor (**NPM**)

BI layout example (Medium Beta)



- Current along pulse: Beam Current Monitor (BCM)
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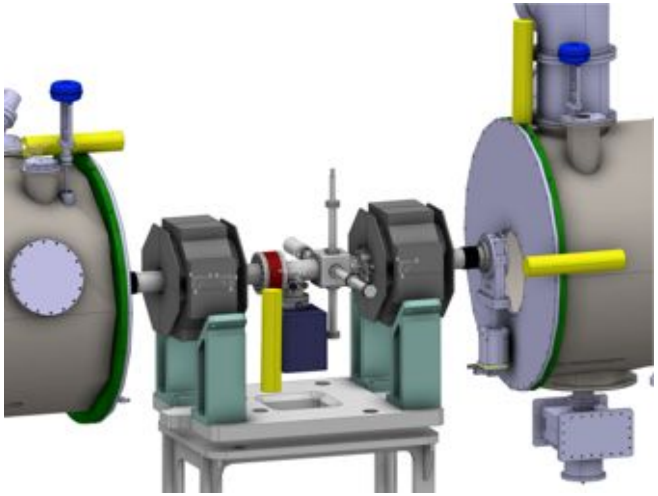


Typical Linac Warm Unit

Beam loss detection

Beam losses and Machine Protection

Beam losses monitoring is mandatory in multi megawatts machine to:

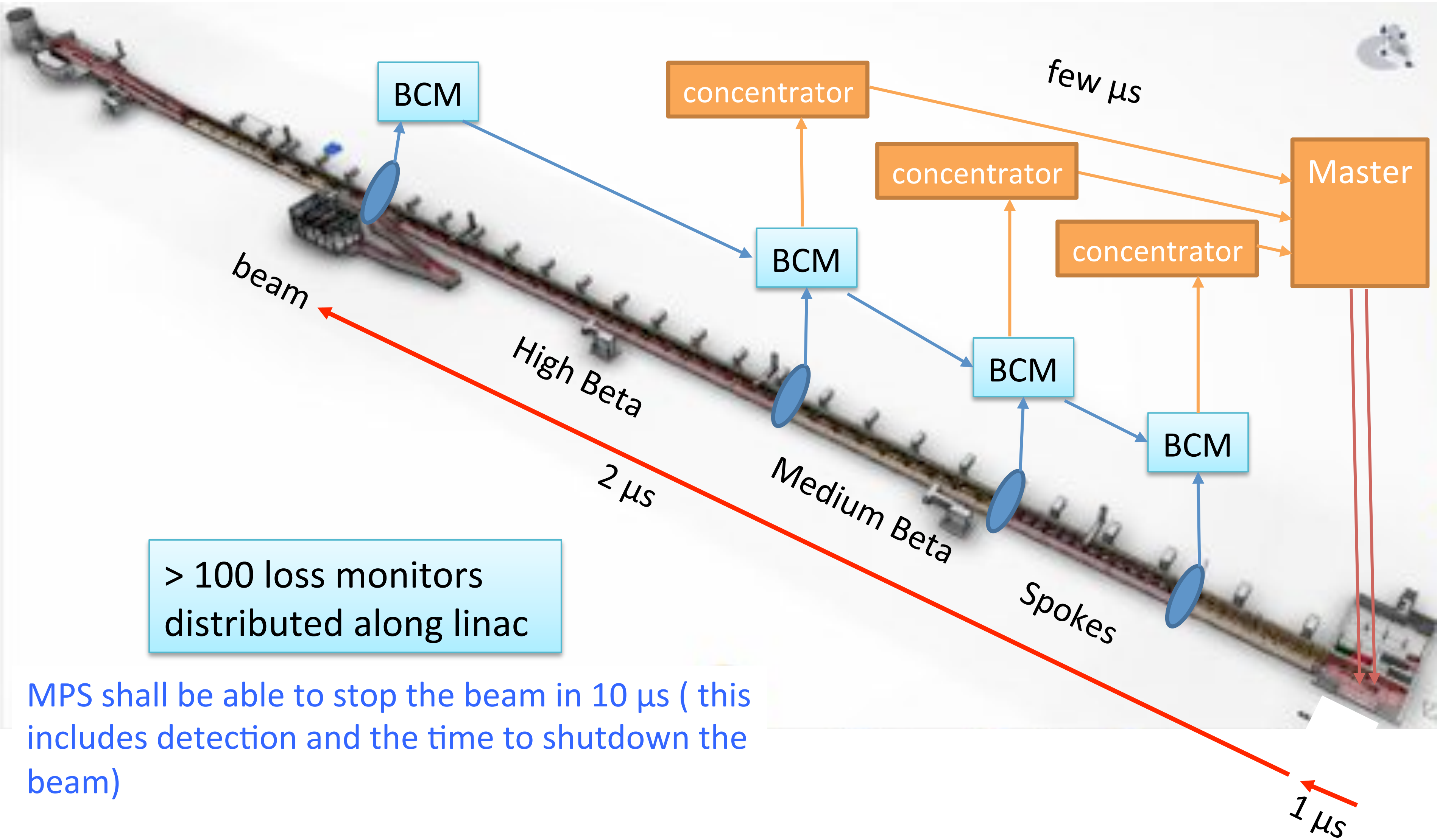
-Protect accelerator components from damages (low energy)

-Prevent activation of the component, loss limit set at 1 W/m (high energy)

@2 GeV, 1W/m corresponds to ≈ 200 protons per bunch loss

- At low energy:
  - Secondary shower not enough energetic to be detectable outside vacuum
  - Loss calculated with beam current transmission (BCM) similar principle as LINAC4 watchdog
  - Neutron detector to measure the integrated dose
- At high energy:
  - Shower detectable by detector outside vacuum
  - Detector based on LHC ionization chamber
  - Cavities background might be an issues

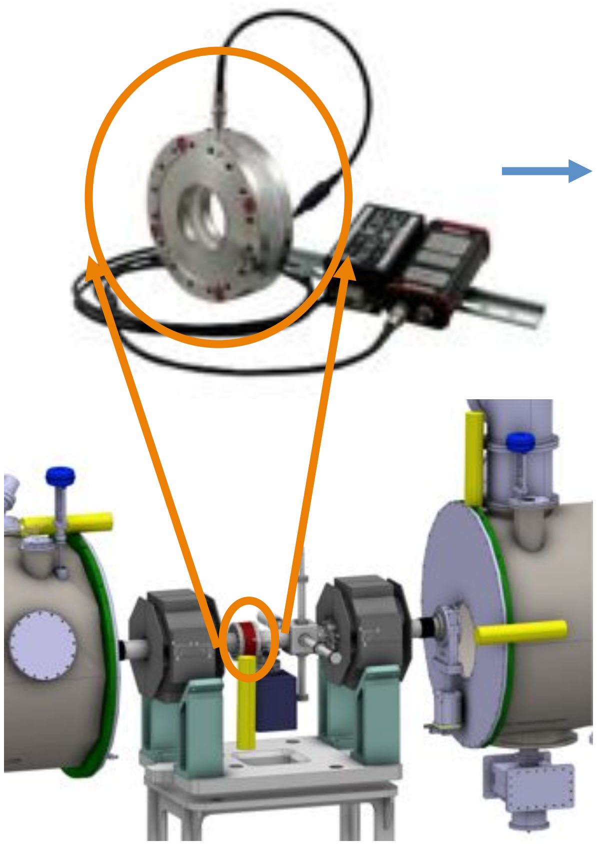
Layout and Latency in ESS Linac

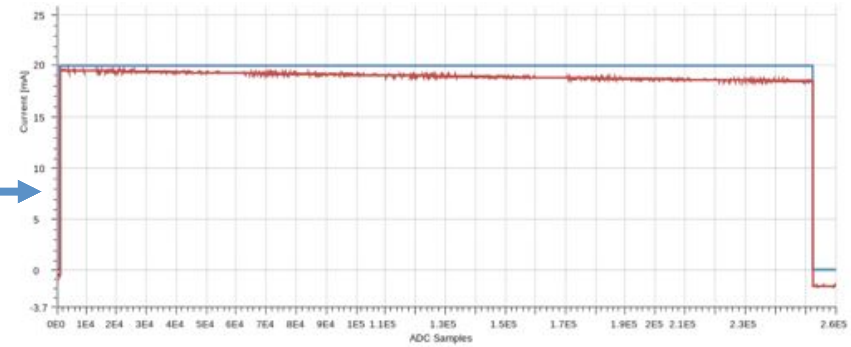


> 100 loss monitors distributed along linac

MPS shall be able to stop the beam in 10 μs (this includes detection and the time to shutdown the beam)

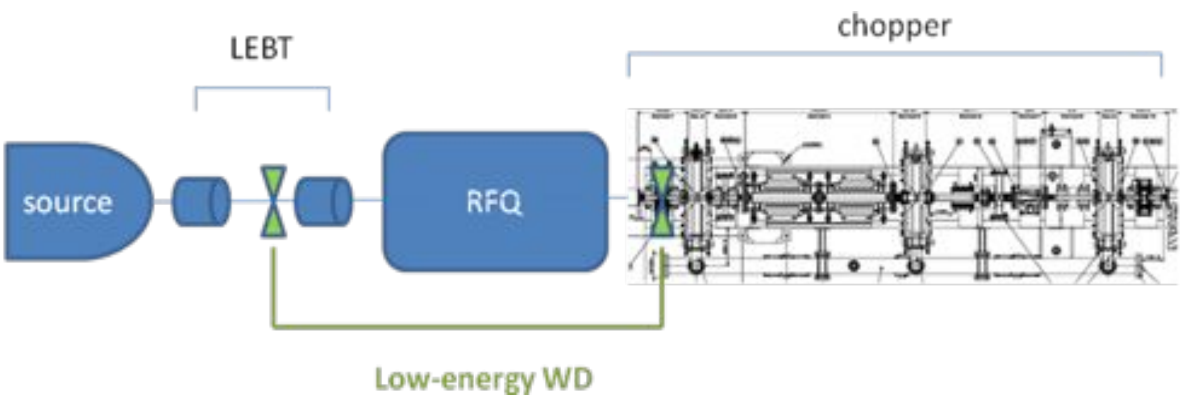
Current Monitor for ESS Linac





Droop correction over long pulse

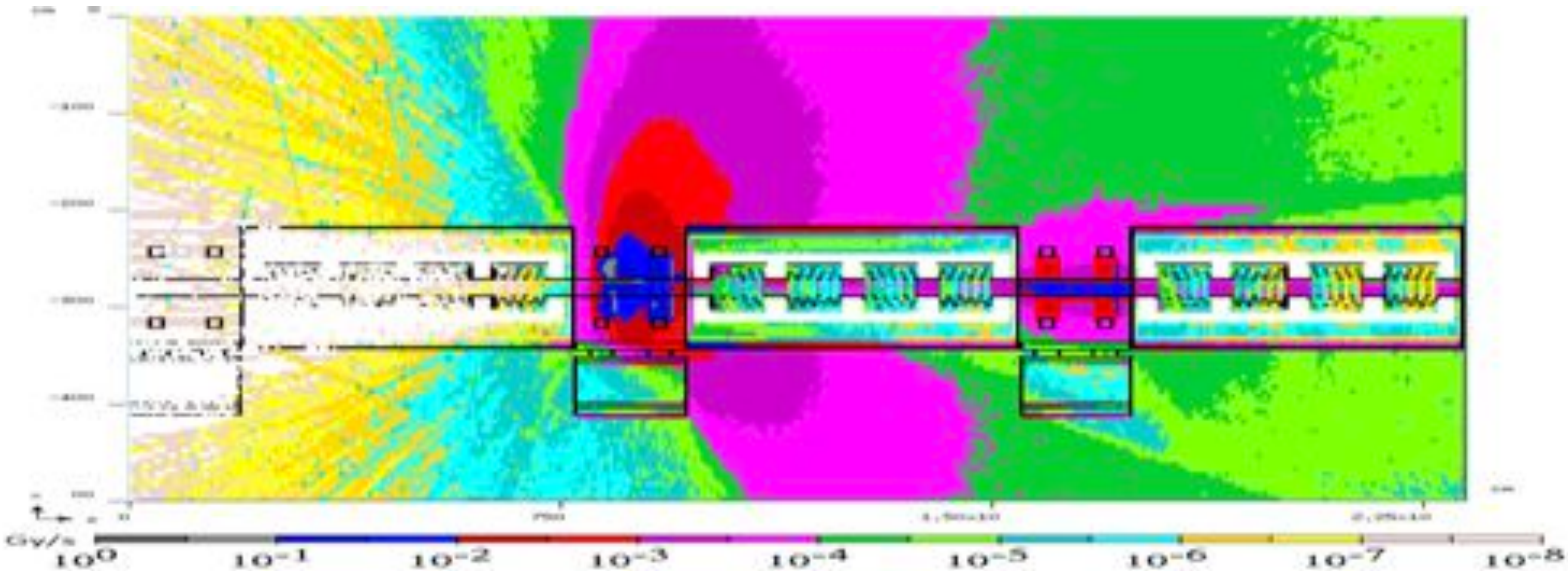
Differential BCM will be primary beam loss measurement in warm linac.



Example of transmission measurement through LINAC4 RFQ (watchdog)

H. Hassanzadegan

Beam Loss map (example)



- Beam loss located in a quad (Medium Beta section)

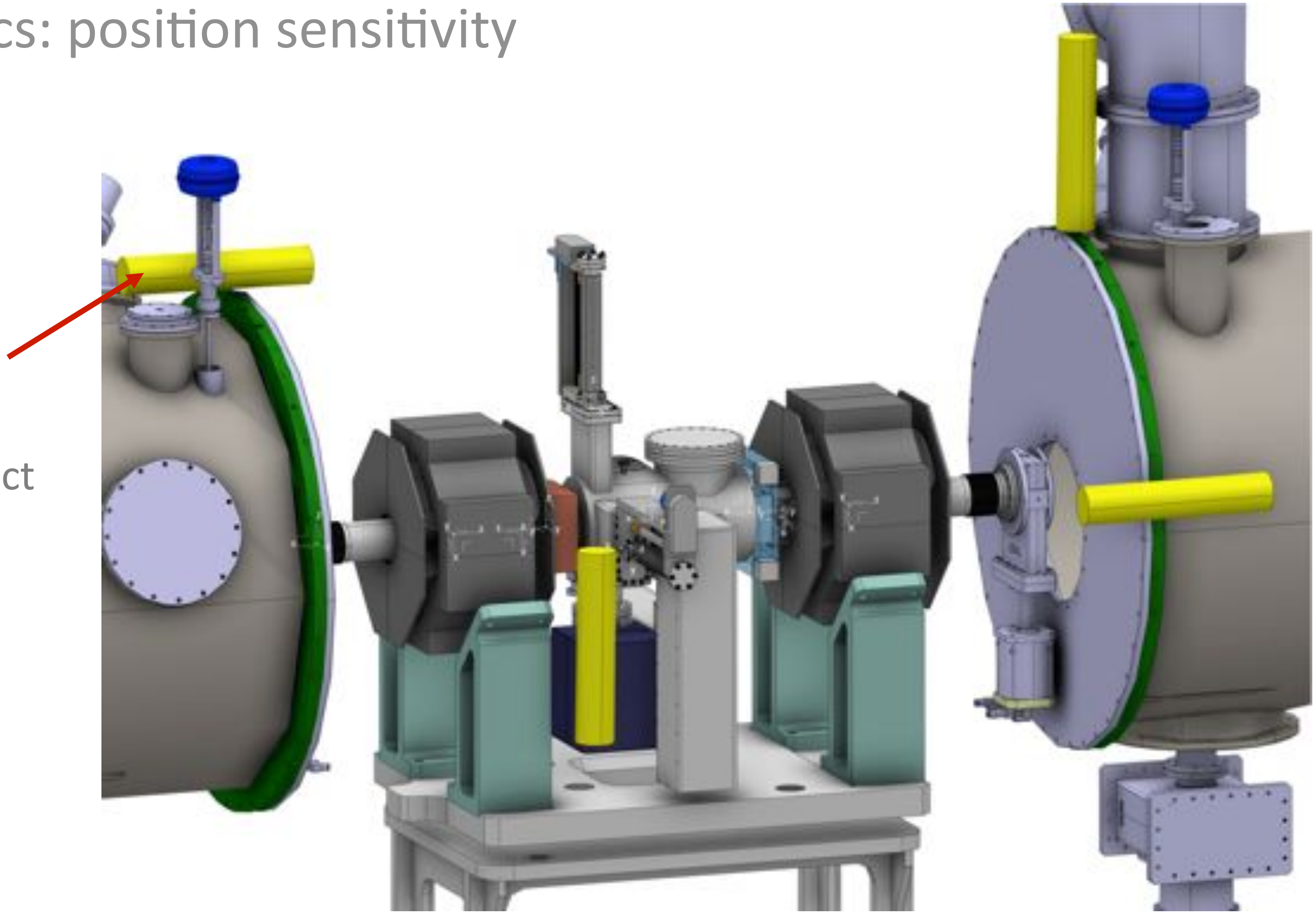
Michal Jarosz

Loss Monitor Placement
ESS Warm Unit

- Protection: full coverage - position insensitivity
- Diagnostics: position sensitivity

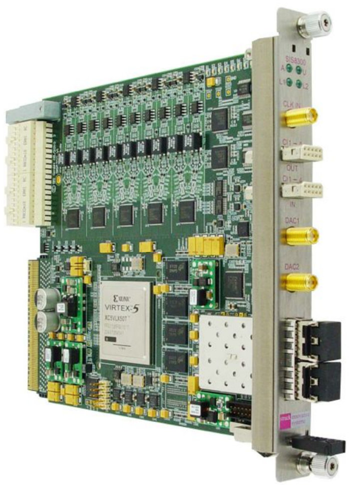
Ion chambers:

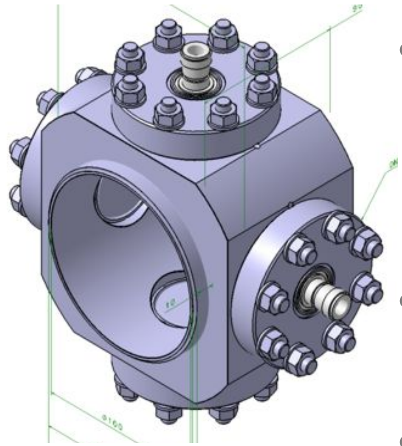
- LHC-style
- a few μs to detect 10% beam loss (including electronics)



General linac diagnostic

Beam Position and Phase





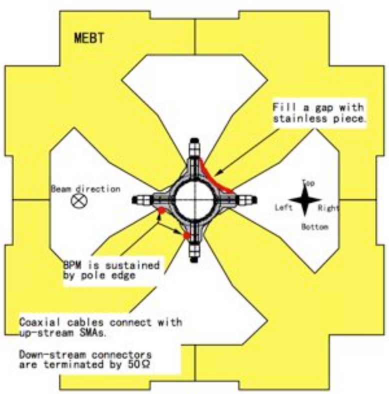
ESS button prototype

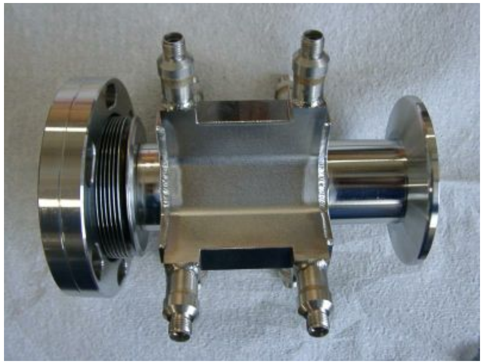
- BPMs are used to steer the beam, but are also the primary tool for setting the cavity phase.
- Requested accuracy: ±100 μm
- Measurement of beam energy with Time of Flight method
- Pickups done by partners.
  - Stripline BPM in the MEBT (ESS Bilbao)
  - Stripline integrated in the drift tube (INFN Legnaro)
  - Button BPM in the cold linac (DESY and Daresbury)

H. Hassanzadegan

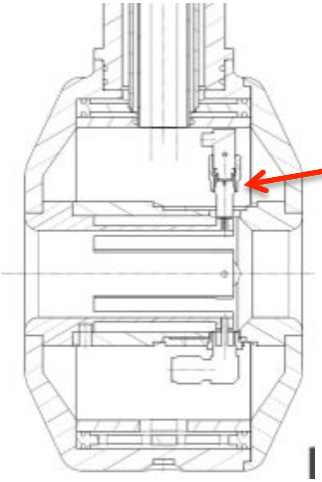
BPMs

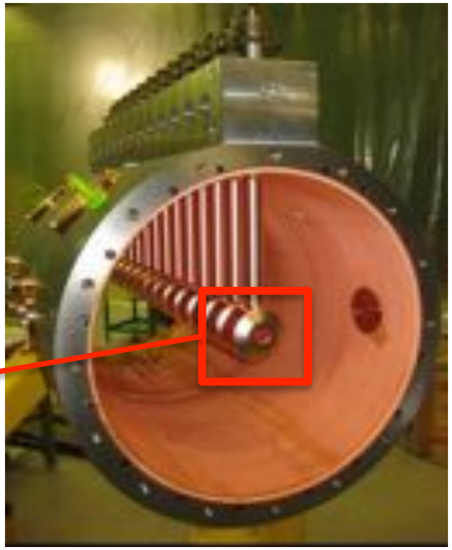
- In the warm linac, mechanical integration is challenging
  - Integration in the MEBT quad
  - Integration in the DTL empty drift tube





Example of BPM integrated in quad (Jparc), the BPM assembly doesn't required extra space (courtesy of Jparc)



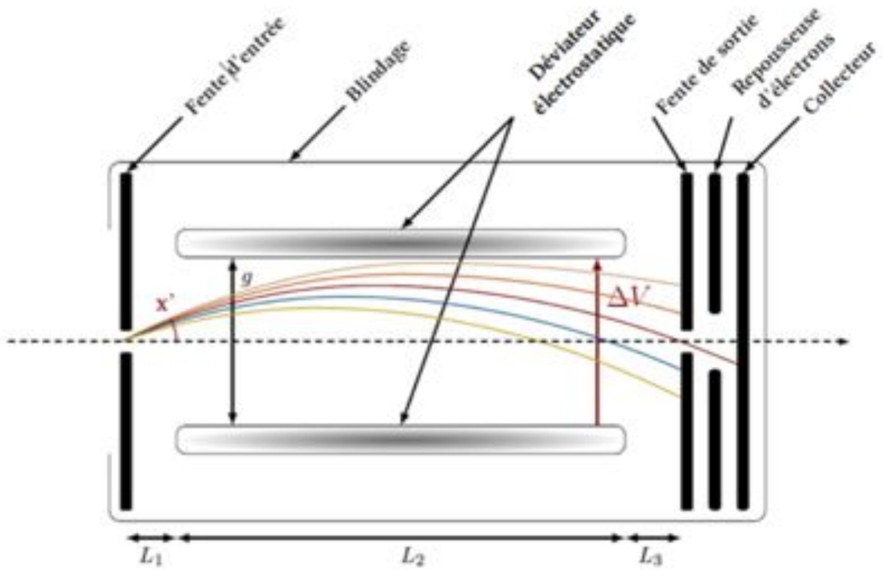


CERN-INFN DTL prototype

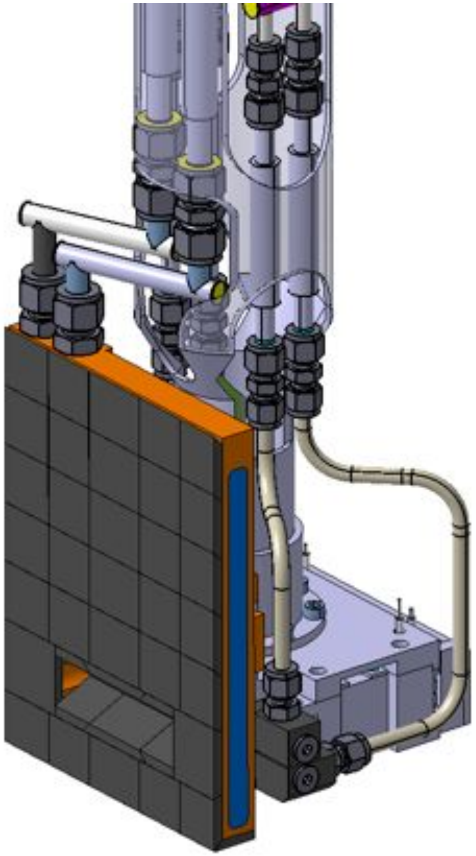
ESS DTL stripline BPM. (Courtesy of INFN legnaro)

Emittance measurement (LEBT and MEBT)

- EMU for LEBT
  - IFMIF-like Allison scanner
  - Design to absorb full beam power



Schematic view of an Allison scanner (CEA/IRFU)

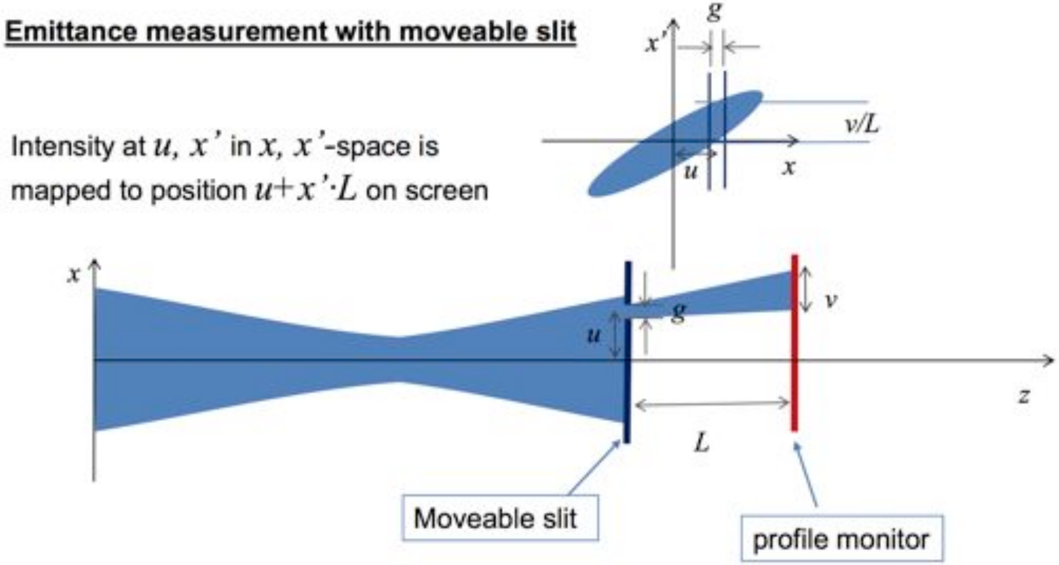


Allison scanned developed at CEA for the ESS LEBT

Emittance measurement (LEBT and MEBT)

- EMU for MEBT
  - Based on slit and grid system (similar LINAC4)
  - Only able to absorb a fraction of the beam power (P_{peak}=230 kW, Pulse max. =50µs)

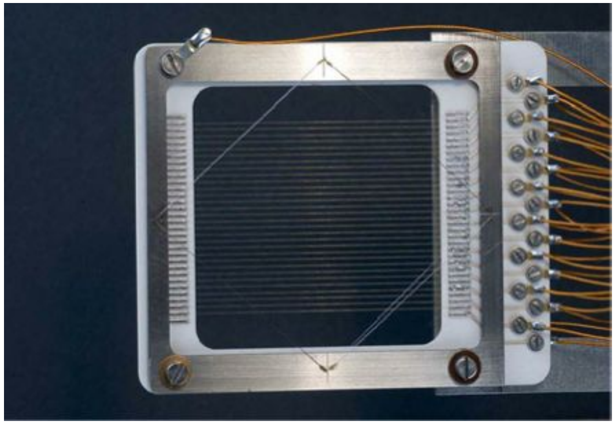
Emittance measurement with moveable slit



From width and position of slit image mean beam angle and divergence of slice at position u is readily computed.

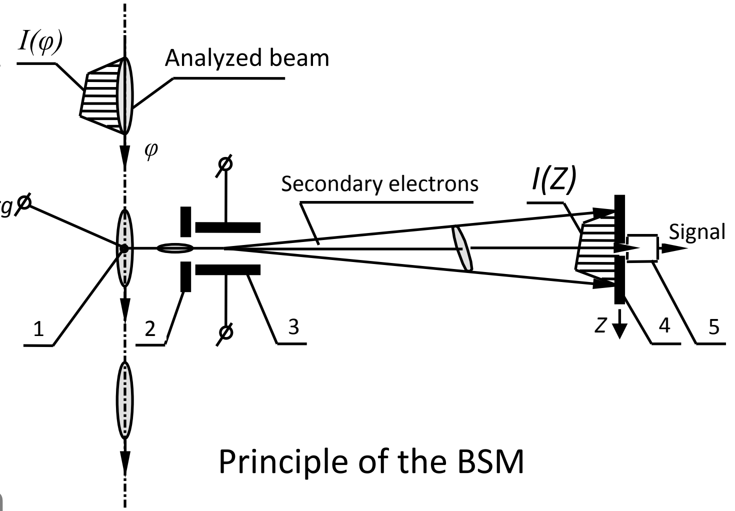
By moving slit across the beam complete distribution in x, x' space is reconstructed.

LINAC4 emittance meter slit and grid

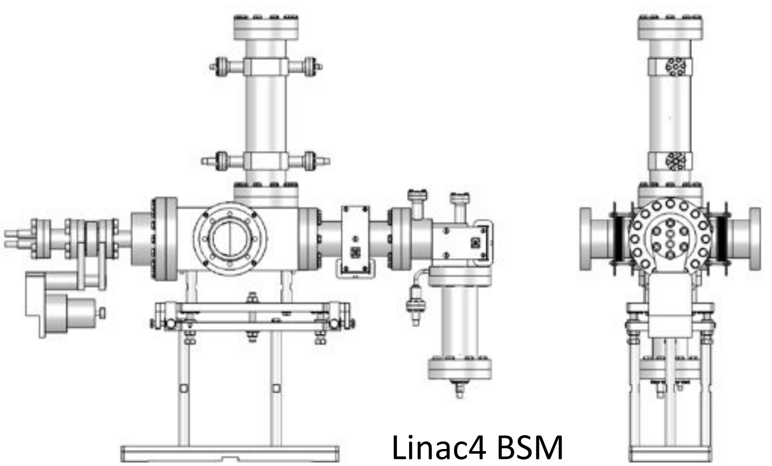


LONG. PROFILE-MEBT/DTL-BSM

- Based on collecting low energy secondary e– emitted from a wire places in the beam
- Temporal bunch structure transformed into spacial distribution of secondary e– through RF modulation
- Intrinsic limitations to resolution due to:
  - Space charge
  - Time dispersion of secondary electron emission (SEE)
    - theoretical value for metals 10^{-14}-10^{-15} s
    - experiments give different upper limits dependin on their accuracy (few ps - few 100 ps)
- well established method (LINAC4, JPARC)
- New development by Feshenko on going tc improve the resolution



Principle of the BSM

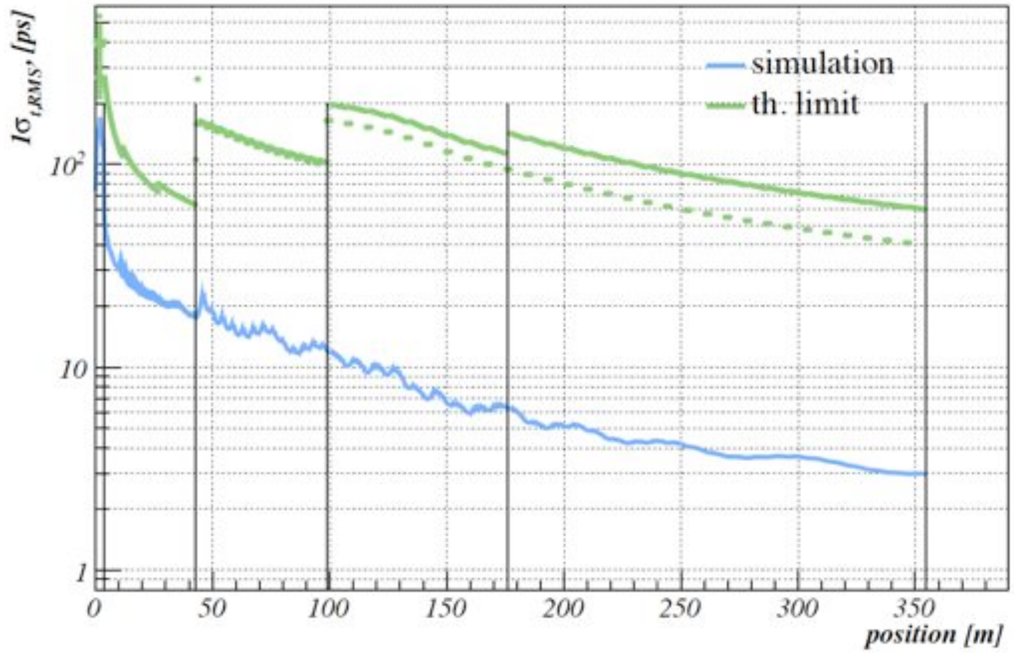


Linac4 BSM

I. Dolenc Kittelmann

High energy BSM

- Expected bunch length along the linac (blue):
  - Spokes: 22 - 12 ps
  - Medium β: 12 - 6 ps
  - High β: 6 - 3 ps
- expected bunch lengths << intrinsic limit for methods based on detection of el. fields at the beam pipe boundary (green)



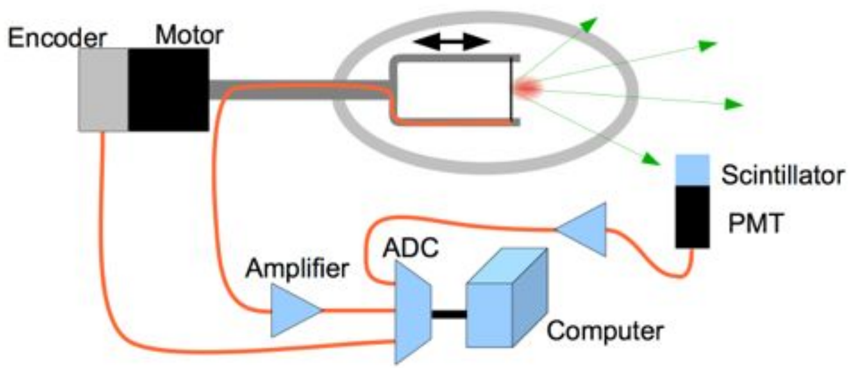
- New method to be developed
  - May need a streak camera
- Based on light detection
  - Cerenkov radiation
  - OTR radiation (might be to low, $\gamma \approx 3.1$ @ 2GeV)

Looking at electron machine diagnostics for sub-picosecond time resolution

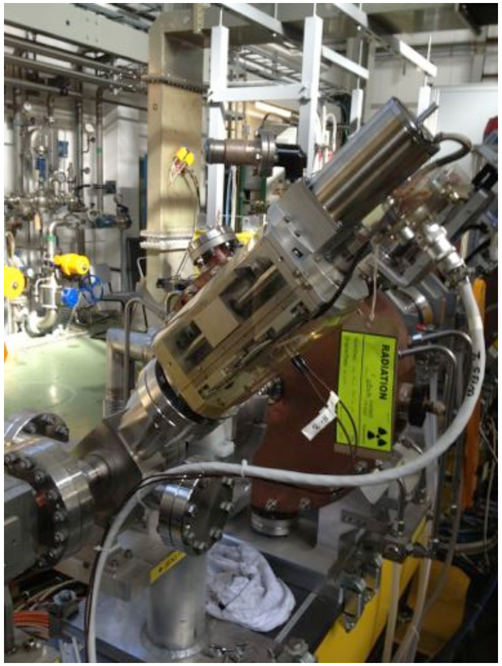
I. Dolenc Kittelmann

Wire Scanner

A thin wire is scanned through the particle beam while the secondary emission current, the signal from a calorimeter downstream, and the signal of the motor encoder are acquired simultaneously. Plotting either of the SEM or PMT signals against the encoder gives the beam profile.



Wire scanner principle

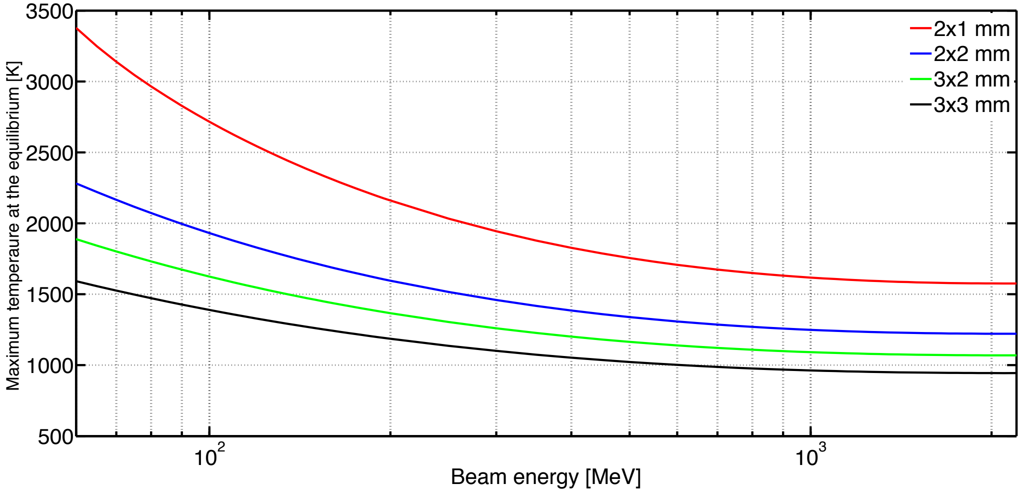


LINAC4 Wire scanner

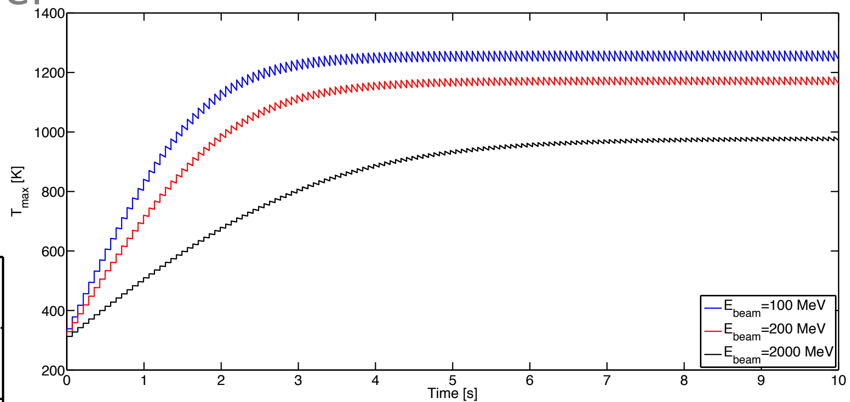
- At ESS:
  - Warm linac: 33 μm carbon wire, SEM mode
  - Spoke section: 40 μm tungsten wire, SEM mode
  - Elliptical section: 40 μm tungsten wire, SEM+shower modes
  - 10^4 dynamic range

Wire scanner issues

- Limitation due to thermal load
- Unable to measure the beam at full power
  - MEBT: up to 50 µs, 1 Hz
  - LINAC: up to 100 µs, 1 Hz
- Cavities background



Maximum temperature at the equilibrium (100 µs, 1 Hz) for a tungsten wire, for beam energies form 60 MeV to 2500 MeV and beam intensity of 62.5 mA.

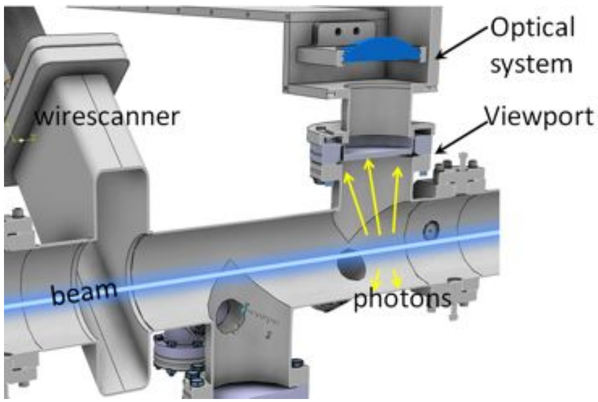


Evolution of the peak temperature on a 40 µm tungsten wire for a 100 MeV beam (blue line), a 200 MeV beam (red line) and a 2000 MeV beam (black line), the beam pulse length is set at 5 µs for a repetition rate of 14 Hz. The wire position is constant (x=0).

Need for Non interceptive Profile Monitor

Non Invasive Profile Monitor (NPM)

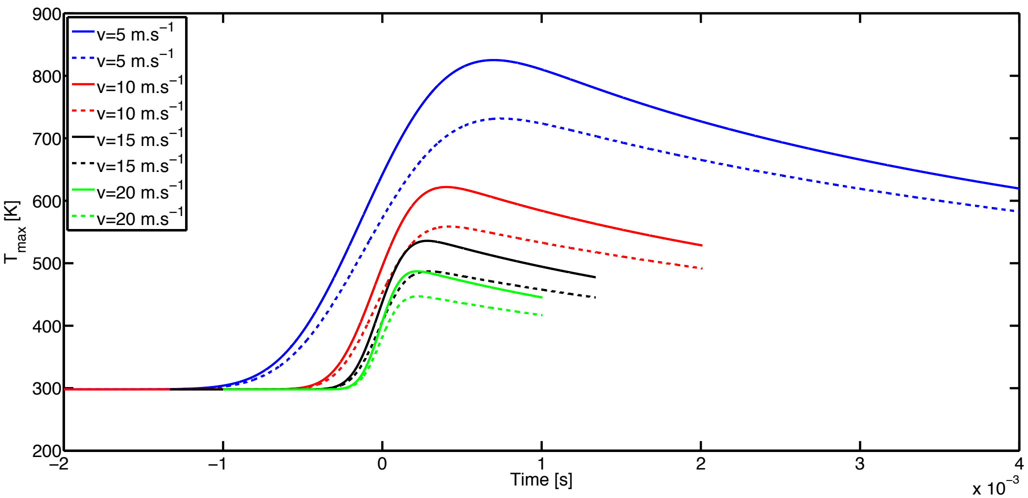
- Signal depends on gas pressure in both cases (low in SC linacs)
  IPM more effective in collecting signal, fluorescence light emitted in 4π solid angle.
- May need high voltage due to beam space charge
- Ionization signal can be collected on anode strips, or converted to photons and measured with camera/multichannel PMT.



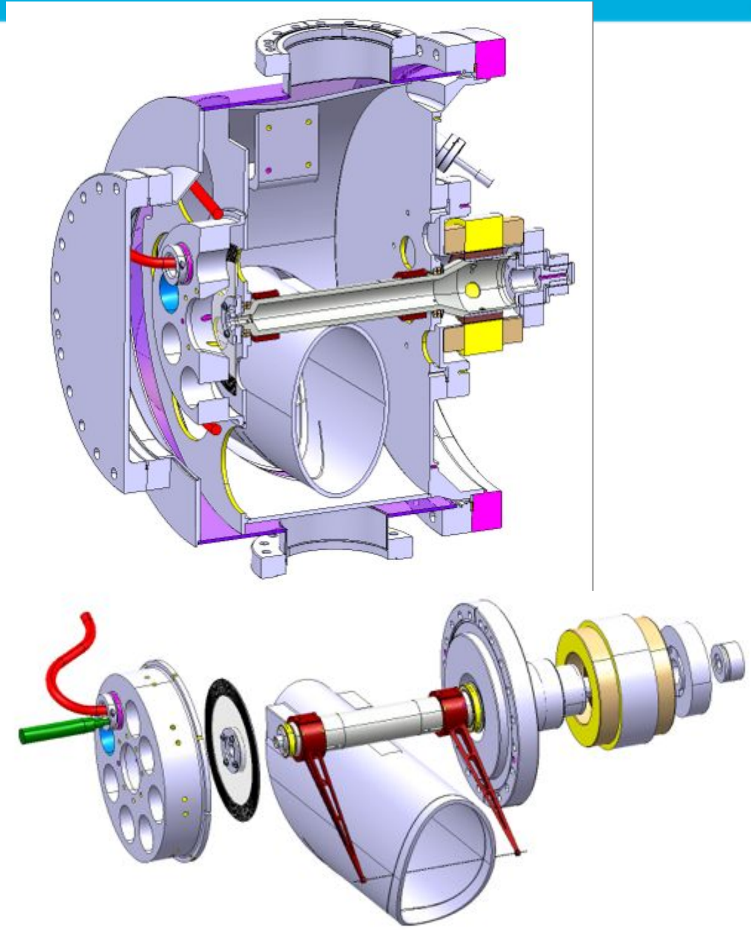
Non-invasive profile methods may not perform well with short pulse, low currents (pilot beams)

Fast wire scanner ("flying wire")

- Possibility of using a fast wire to measure beam profile in one pulse in HEBT
    - Carbon
    - Only shower mode
    - Detector geometry similar to elliptical wire scanner
- Mechanical design done at CERN for the upgrade of accelerator complex



Evolution of wire peak temperature during a scan at 560 MeV (solid line) and 2000 MeV (dashed line) for different wire velocity.



Design of the new CERN flying wire scanner (courtesy of CERN BI group)

Beam instrumentation summary

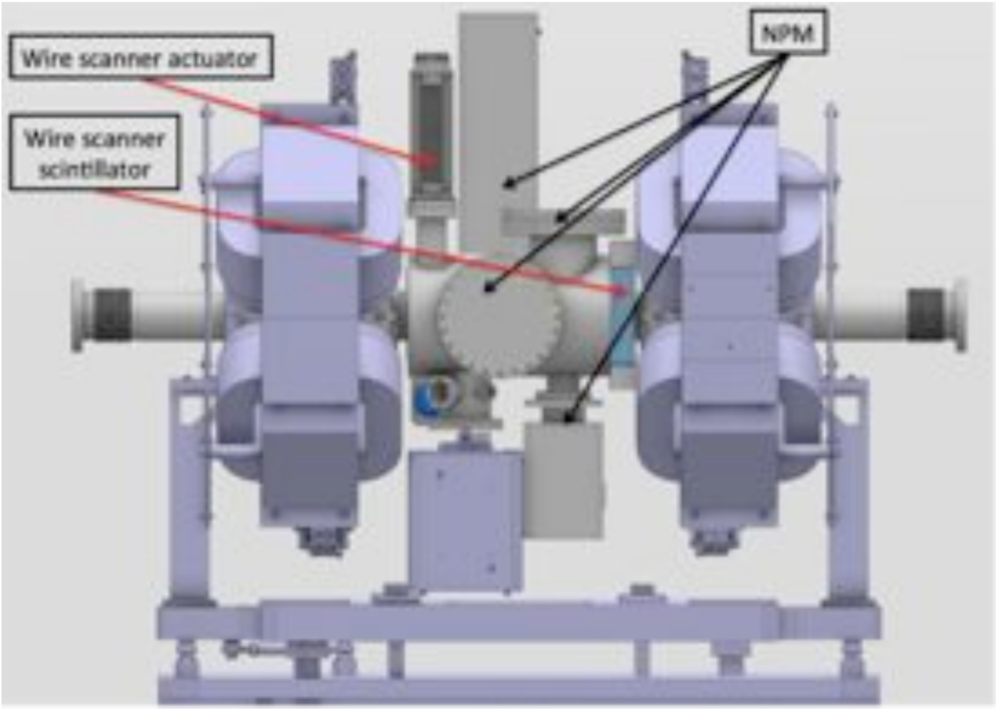
- High power hadron machines pose particular challenges:
  - Keep loss level at low level
  - Interceptive devices are not able to withstand the full beam power
  - Space charge dominated beam, issues for integration and IPM
  - Ultra short bunch length with low β beam, R&D phase needed

- Potential collaboration with Uppsala U.
  - development of the shower detector for the wire scanner system

Potential collaboration with Uppsala U.

Introduction

- Above ≈200 MeV, the secondary emission might be too weak to reconstruct the beam profile. The reconstruction can be done by measuring the shower created in the wire.



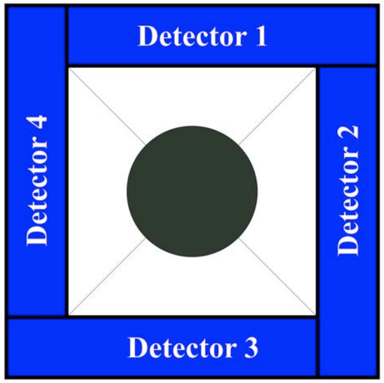
Preliminary layout of a typical Linac Warm Unit (LWU) foreseen to be installed in the elliptical and HEBT section.

Scintillator can be seen as a Calorimeter, light collection efficiency must be known and optimized in order to defined the acquisition electronic.

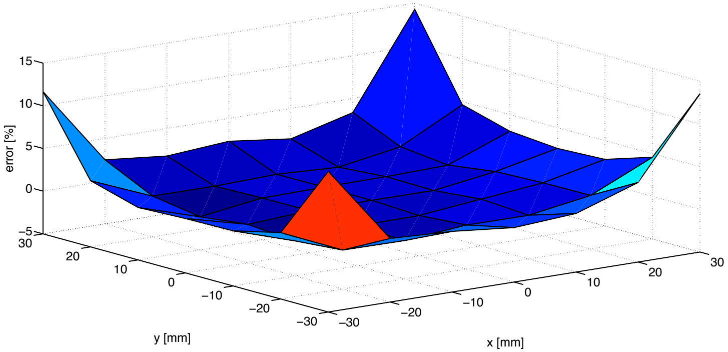
Cavities background might be an issue.

Detector-first simulations

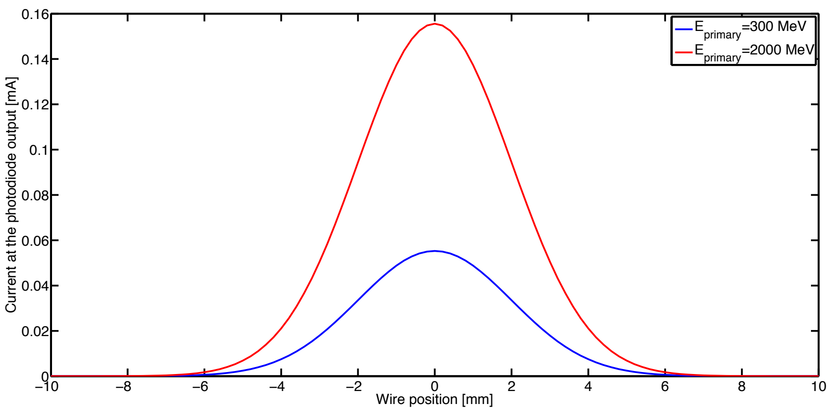
- Detection of hadronic shower created by the wire
  - Monte Carlo simulation on going
  - Detector:
    - BGO crystal + photodiode
    - BGO crystal + silicon APD
- Gamma background might be an issue



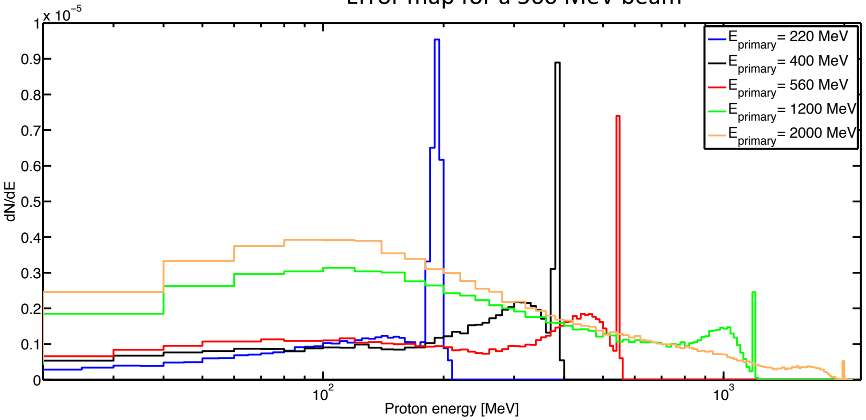
Detector geometry, in blue the scintillators and in black the beam pipe, the diameter of the beam pipe is 100



Error map for a 560 MeV beam



Estimated signal at the output of a typical photodiode coupled with a BGO scintillator, assuming 2% light collection efficiency.



Energy spectrum of proton reaching the detector surface.

Light collection

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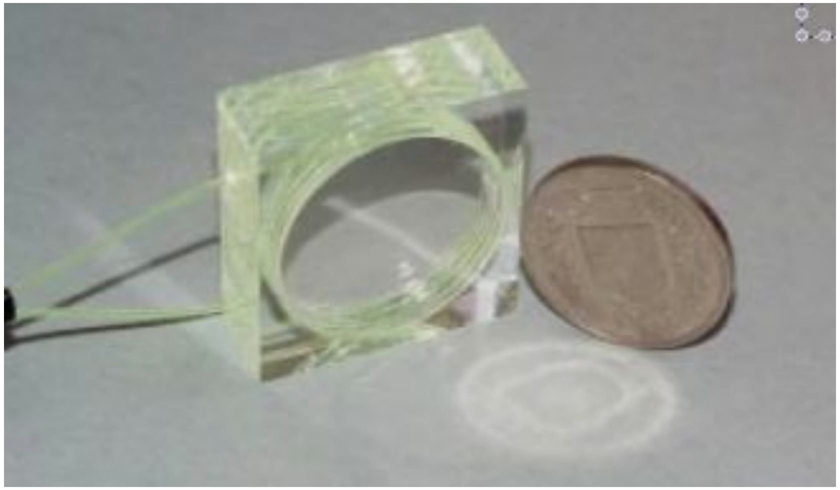
- Several option
  - Direct readout with a photodiode
    - Light collection ≈40%
    - Signal ≈ mA range
  - Coupling with a WLS fiber
    - LSO crystal or plastic scintillator
    - Si APD or PMT (depending on light power on the photodetector)
    - Light collection ≈1%
  - Detection of Cerenkov light
    - In case of background due to cavities
    - Direct connection of PMT or with WLS fiber
- Simulation and prototyping phase needed
  - Estimation of light collection efficiency
  - Test in RF bunker with ESS cavities
  - Possibly test with beam

Ideas for simulations/prototypes

- BGO crystal with a direct photodetector coupling.
- BGO crystal with a direct photodetector coupling and a WLS fiber(s) for Cherenkov detection
- A quartz plate with a WLS fiber for Cherenkov detection
- Plastic scintillator and/or LSO crystal with a single straight WLS fiber
- Plastic scintillator and/or LSO crystal with a single WLS fiber positioned like the LHCb PSD.



LHCb PSD prototype (plastic scintillator and WLS fiber)

Proposal for the upgrade of CMS Hadronic EndCap Calorimeter (quarts plate and UV fibers)

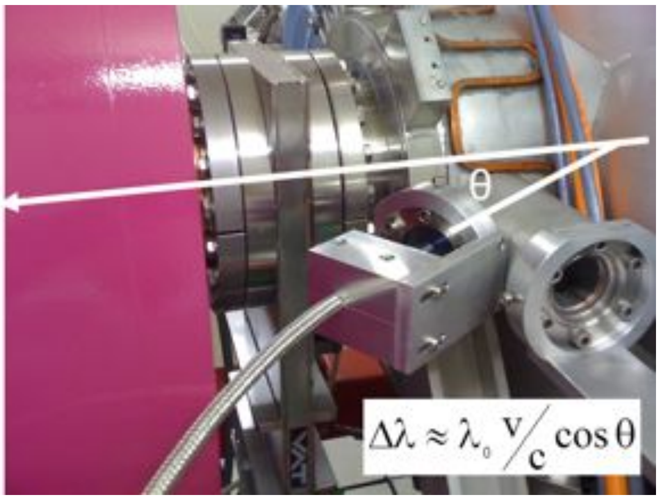
Conclusion

- This presentation was a non exhaustive view of the BI project of ESS, due the presenter bias, still miss :
    - Halo monitoring
    - Beam on target
    - Faraday cup
    - ….
- R&D to be done in the next years
    - High energy bunch length
    - Scintillator readout
    - …
- Collaborations are more than welcome

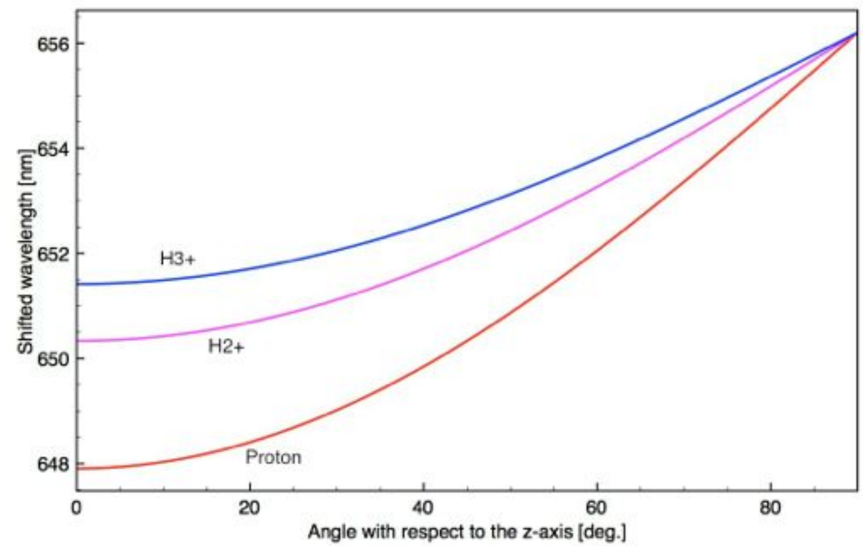
Thanks for your attention

Extra slides

Doppler measurement



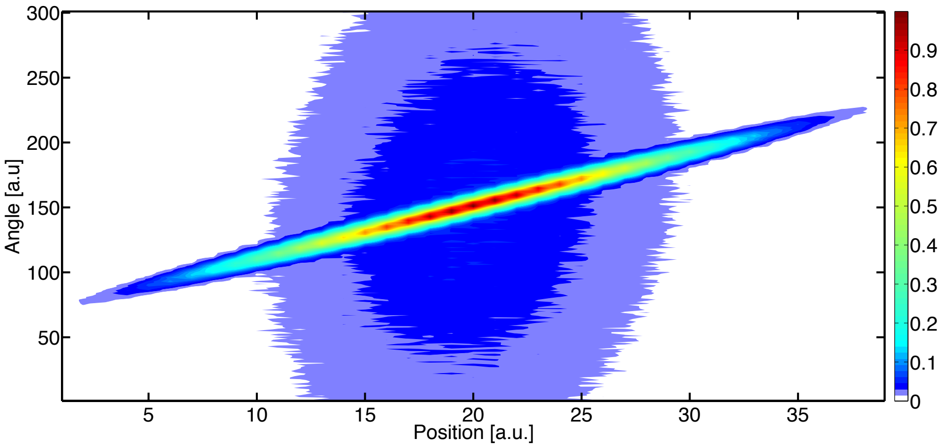
Doppler shift method on the LEBT of the IFMIF source



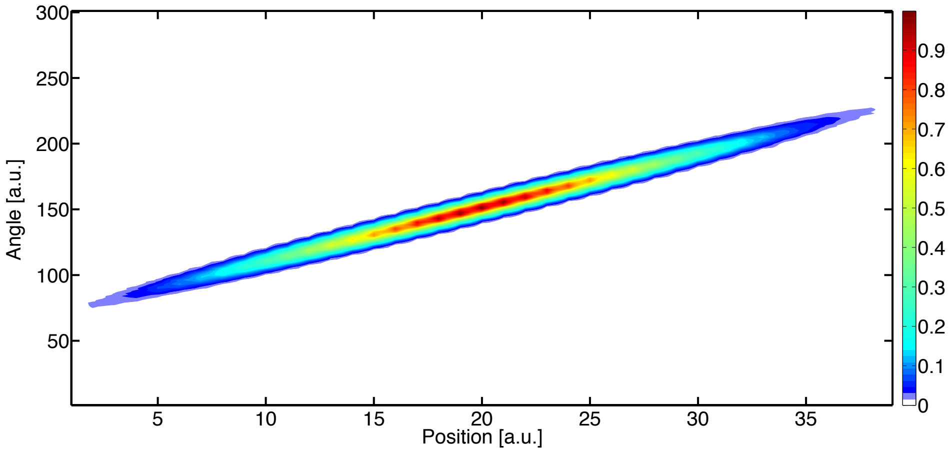
Expected wavelength shift as function of the angle, extracted beam energy equal to 75 keV

After the source, the beam will contain different ions species(protons, H_2^+, H_3^+), at different velocities. The proportion of the different ions can be reconstructed by measuring the Doppler shift with a monochromator.

Scattering effect on emittance measurement



Example of phase space reconstruction with a slit thickness shorter than the proton penetration depth



Example of phase space reconstruction with a slit thickness larger than the proton penetration depth

- Slit thickness shall be larger than proton range in slit material

PMQ and drift tube prototype

Courtesy of INFN Legnaro

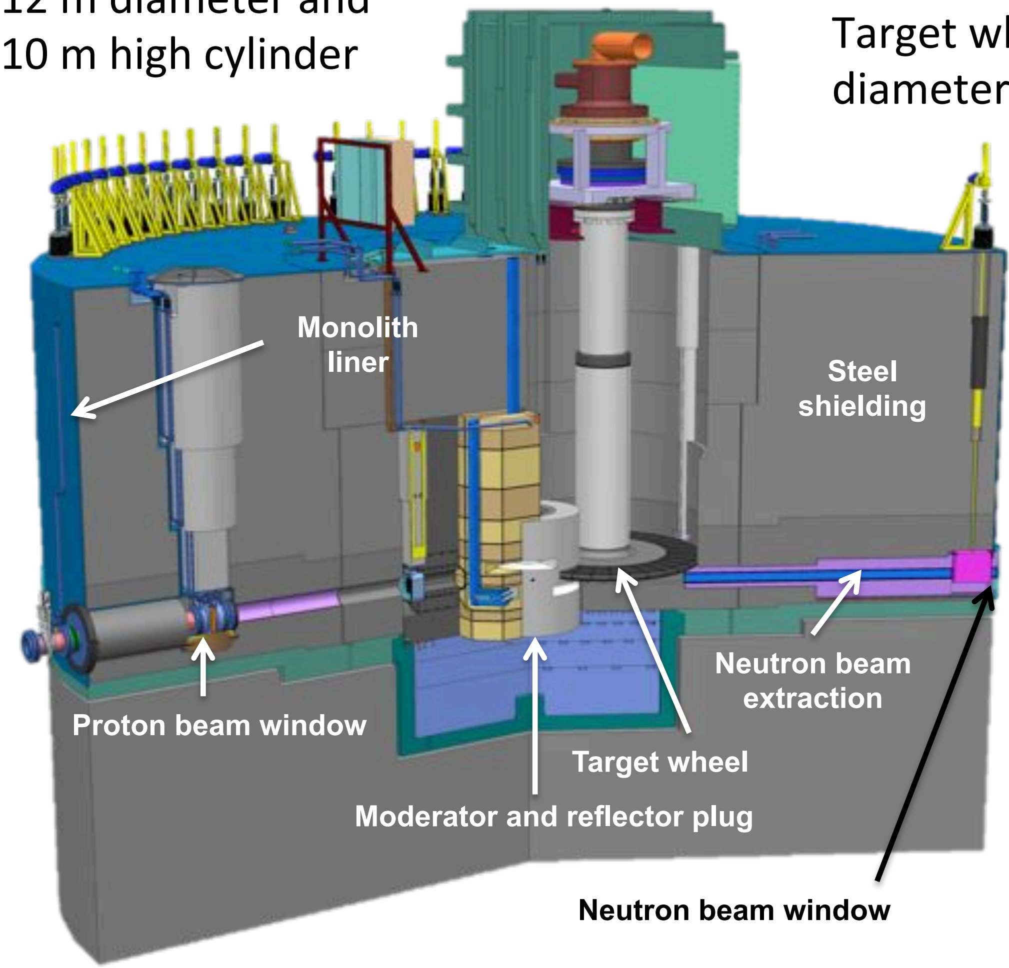
Target station

12 m diameter and
10 m high cylinder

Target wheel of 2,5m of
diameter

7000 tons of steel

Atmospheric-
pressure inert
helium gas



NEUTRON SCIENCE AND INSTRUMENTS

- 22 Instruments
- Initial limited instrument suite available for fully open user program by 2023, and significant number of instruments by start of steady-state ops in 2026