Instrumentation for High Intensity Proton Machines

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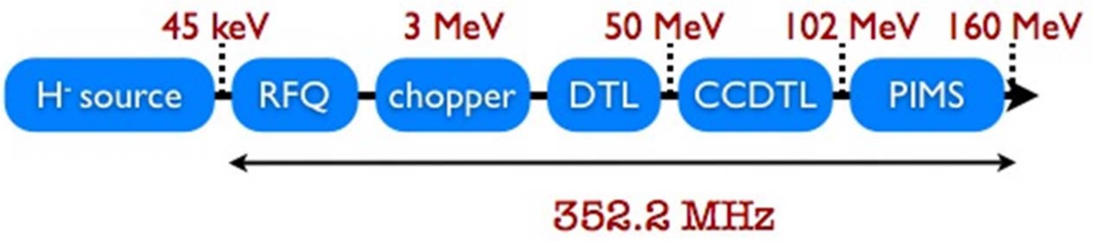
CERN BE/BI

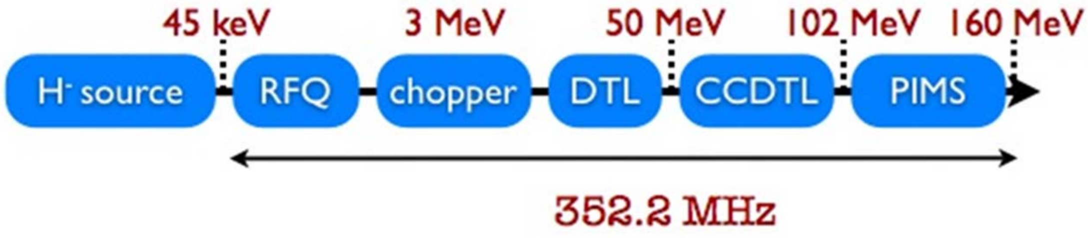
Typical high intensity accelerator front end



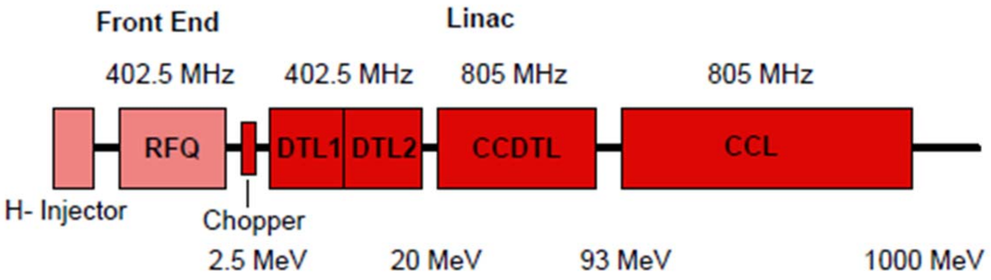
- Ion source
- Radio Frequency Quadrupole
- Chopper
- Different linear accelerator structures
- Transfer line to circular accelerators

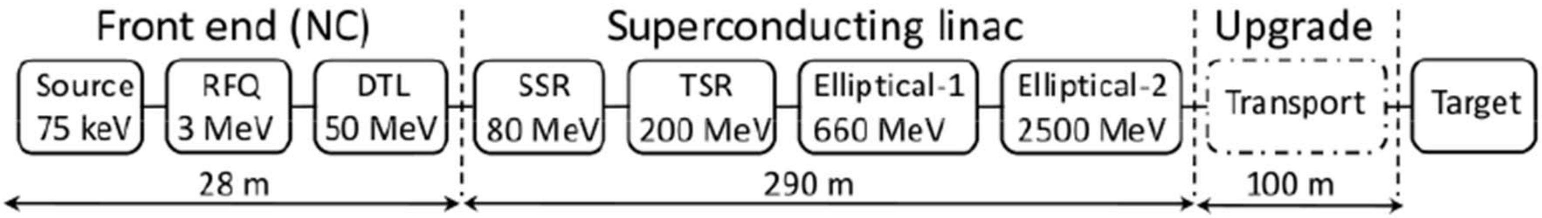
Comparison of Machines

CERN Linac-4



Spallation Neutron Source Oakridge





Comparison of Beam Parameters

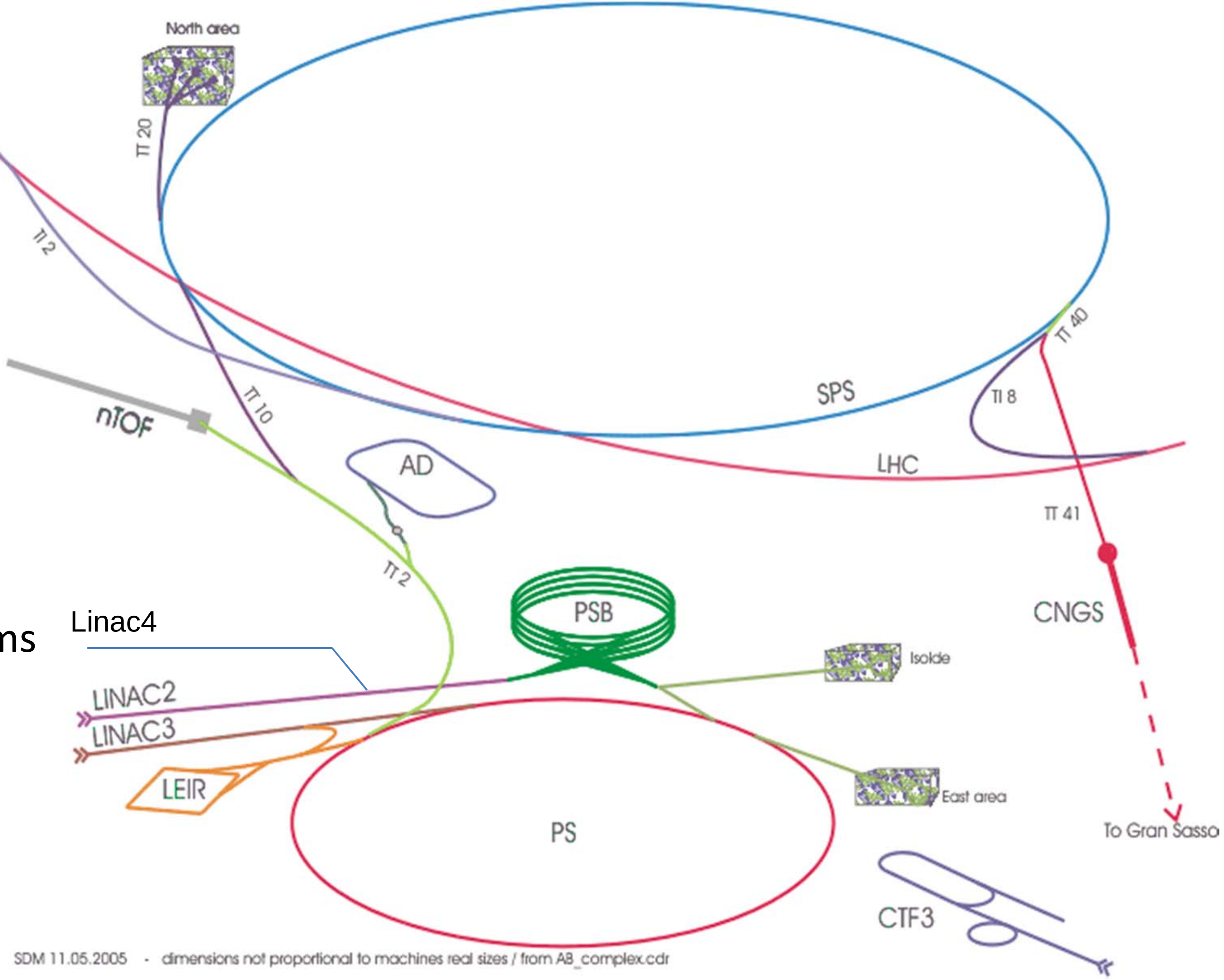
	CERN Linac-4	**Oakridge SNS**	**ESS Scandinavia**
Particle Type	H^-	H^-	P
Energy	160 MeV	1 GeV	2.5 GeV
Average Beam Power	2.8 kW	1.4 MW	5 MW
Pulse Frequency	0.8 Hz	30 Hz	20 Hz
Beam Loss	< 1W/m	<1W/m	<1W/m
Ion Source current	80 mA	48 mA	50 mA
Pulse Length	400 µs – 1 ms	1ms	2ms
RF Frequencies	350 MHz	402.5 MHz	352.2 & 704.4 MHz

Linac-4 in the CERN complex

Linac-4 will inject into the PS Booster (PSB)

Purpose:

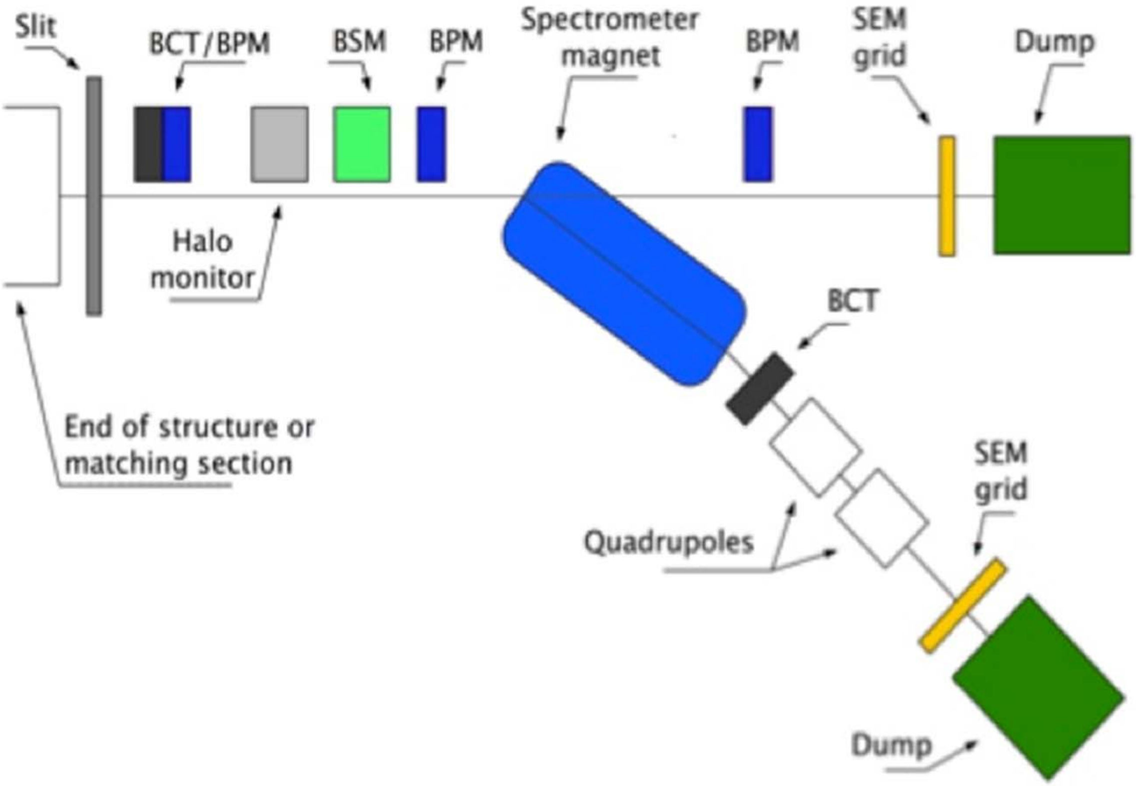
- Improve brightnes of beams for LHC
- Replace aging Linac2



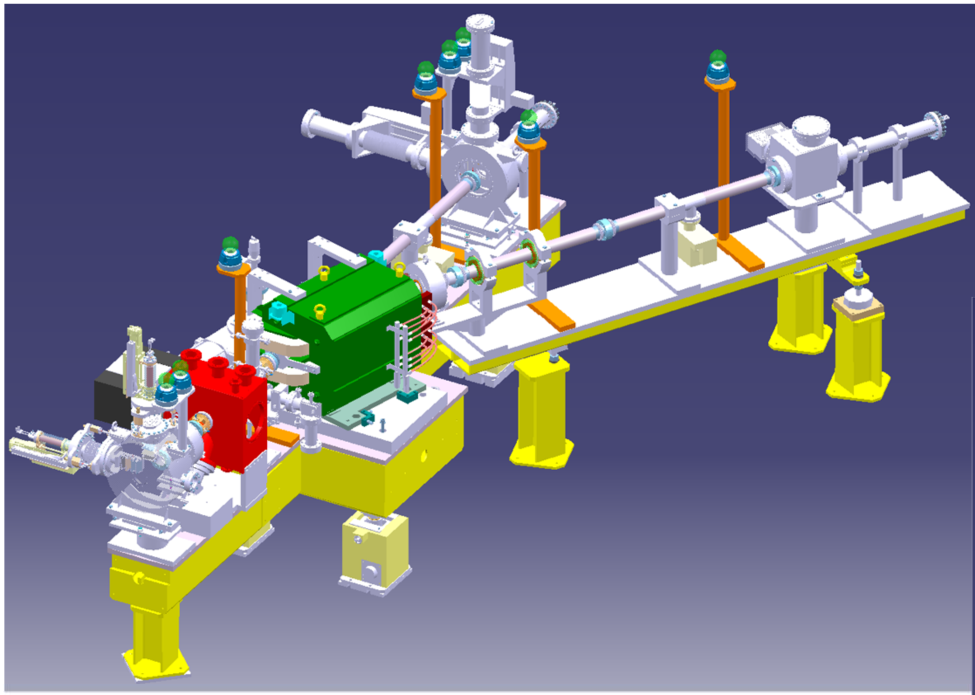
Beam Parameters to be measured

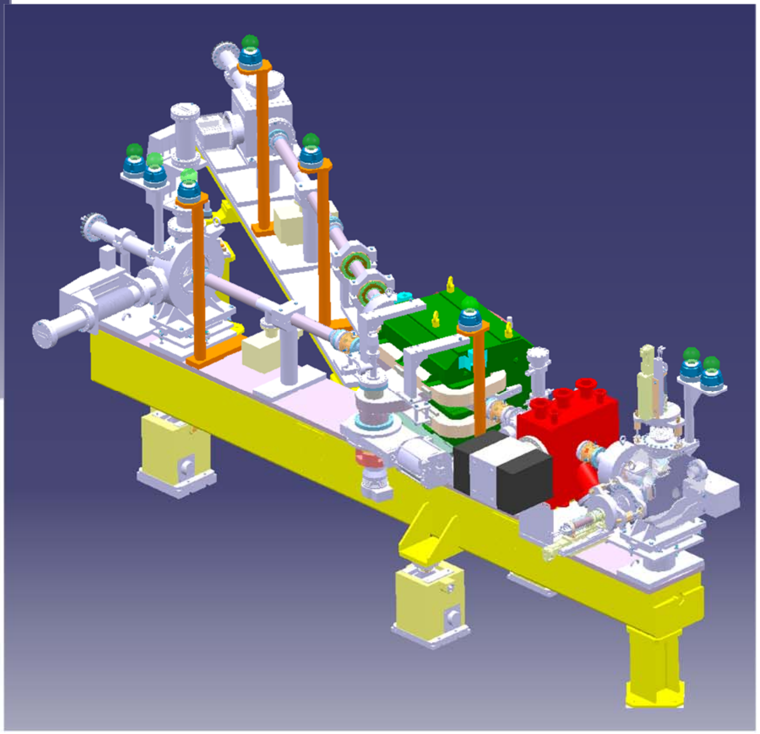
- Beam intensity
- Beam position
- Beam profile
- Beam phase & energy
- Energy spread
- Transverse Emittance
- Longitudinal bunch shape
- Effectiveness of chopper

Measurement Bench



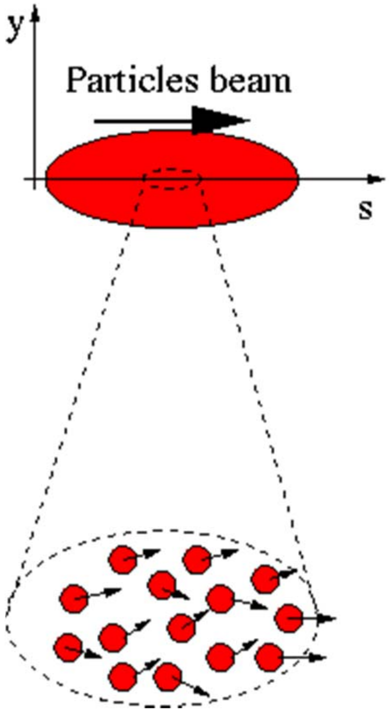
Measurement Bench





Position measurement using BPMs
Intensity measurement using Transformers
Energy spread measurement, Spectrometer
Emittance meter
Bunch shape monitor
Halo monitor

Emittance measurements

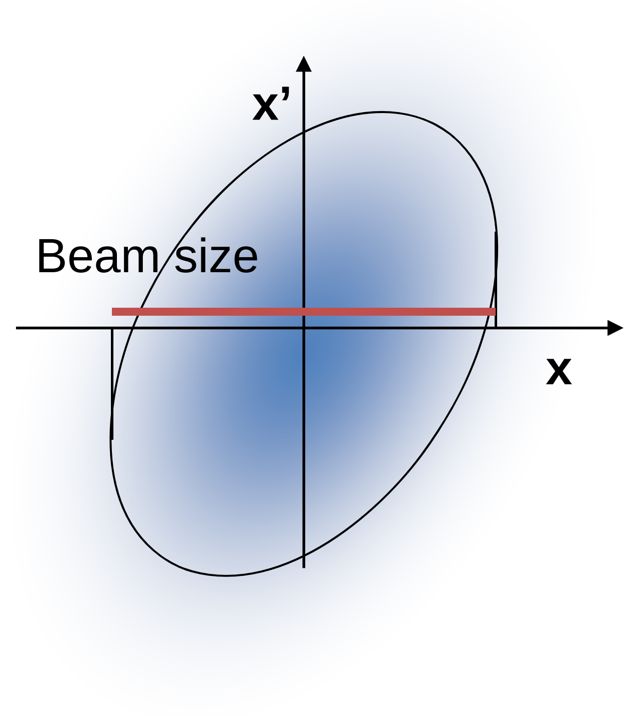


A beam is made of many many particles, each one of these particles is moving with a given velocity. Most of the velocity vector of a single particle is parallel to the direction of the beam as a whole (s). There is however a smaller component of the particles velocity which is perpendicular to it (x or y).

$$\vec{v}_{particle} = v_s \hat{u}_s + v_x \hat{u}_x + v_y \hat{u}_y$$

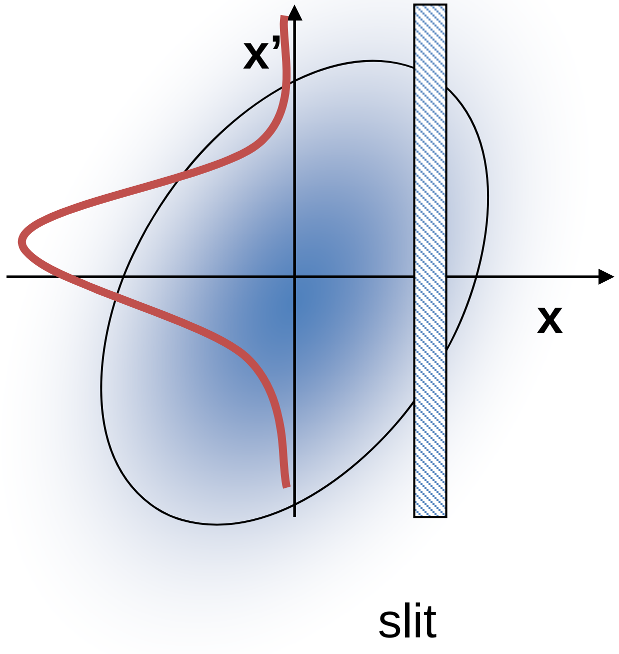
Emittance measurements

- If for each beam particle we plot its position and its transverse angle we get a particle distribution who's boundary is an usually ellipse.
- The projection onto the x axis is the beam size



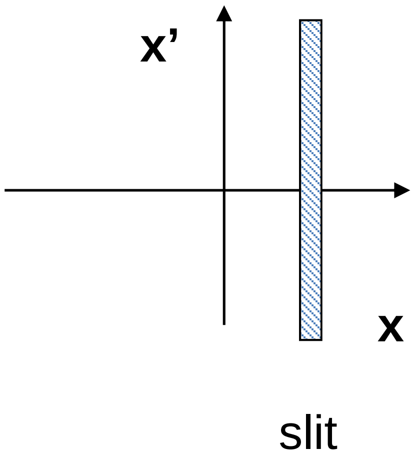
The slit method

- If we place a slit into the beam we cut out a small vertical slice of phase space
- Converting the angles into position through a drift space allows to reconstruct the angular distribution at the position defined by the slit

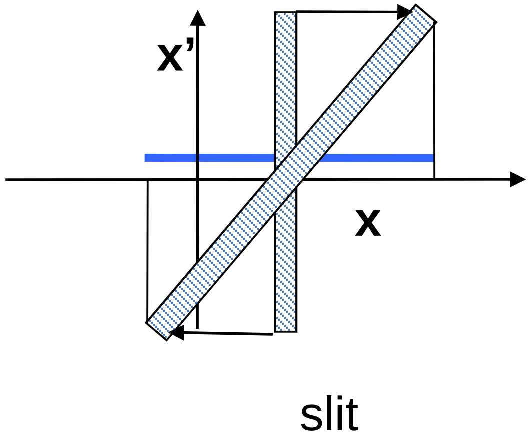


Transforming angular distribution to profile

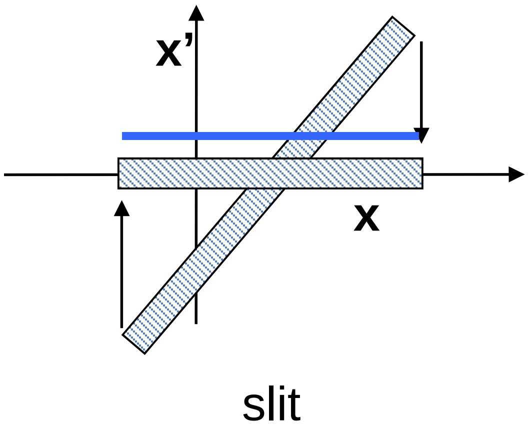
- When moving through a drift space the angles don't change (horizontal move in phase space)
- When moving through a quadrupole the position does not change but the angle does (vertical move in phase space)



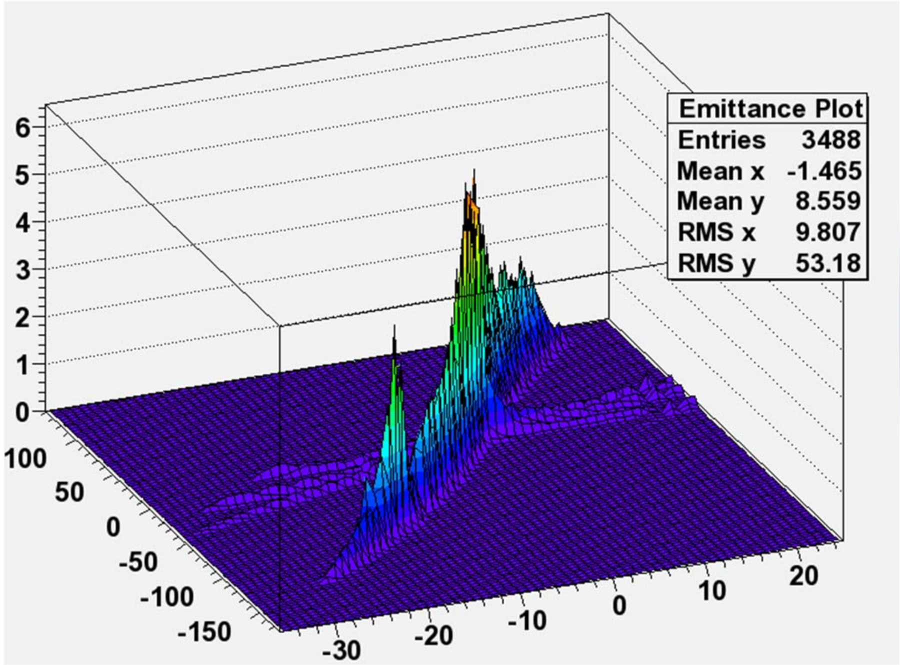
Influence of a drift space



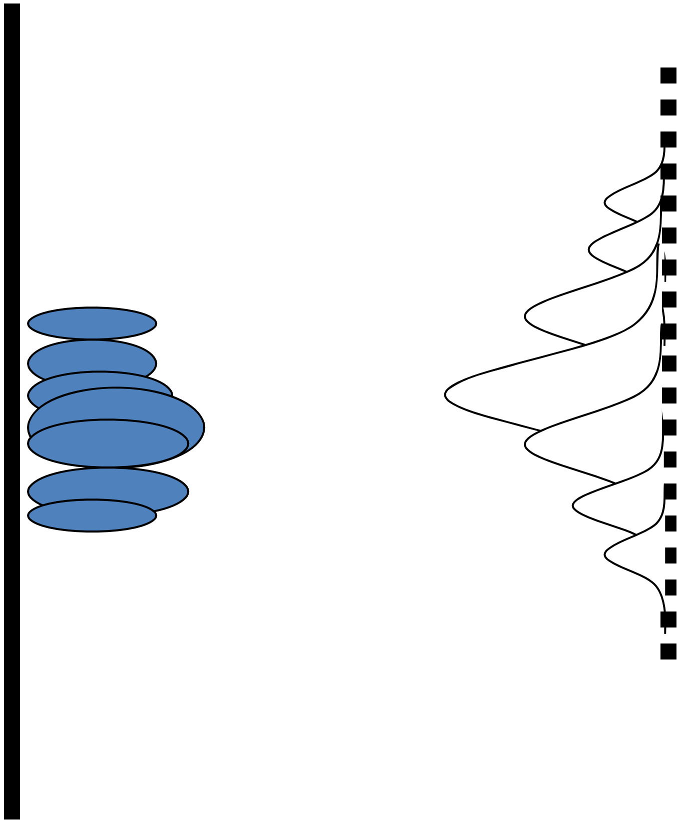
Influence of a quadrupole



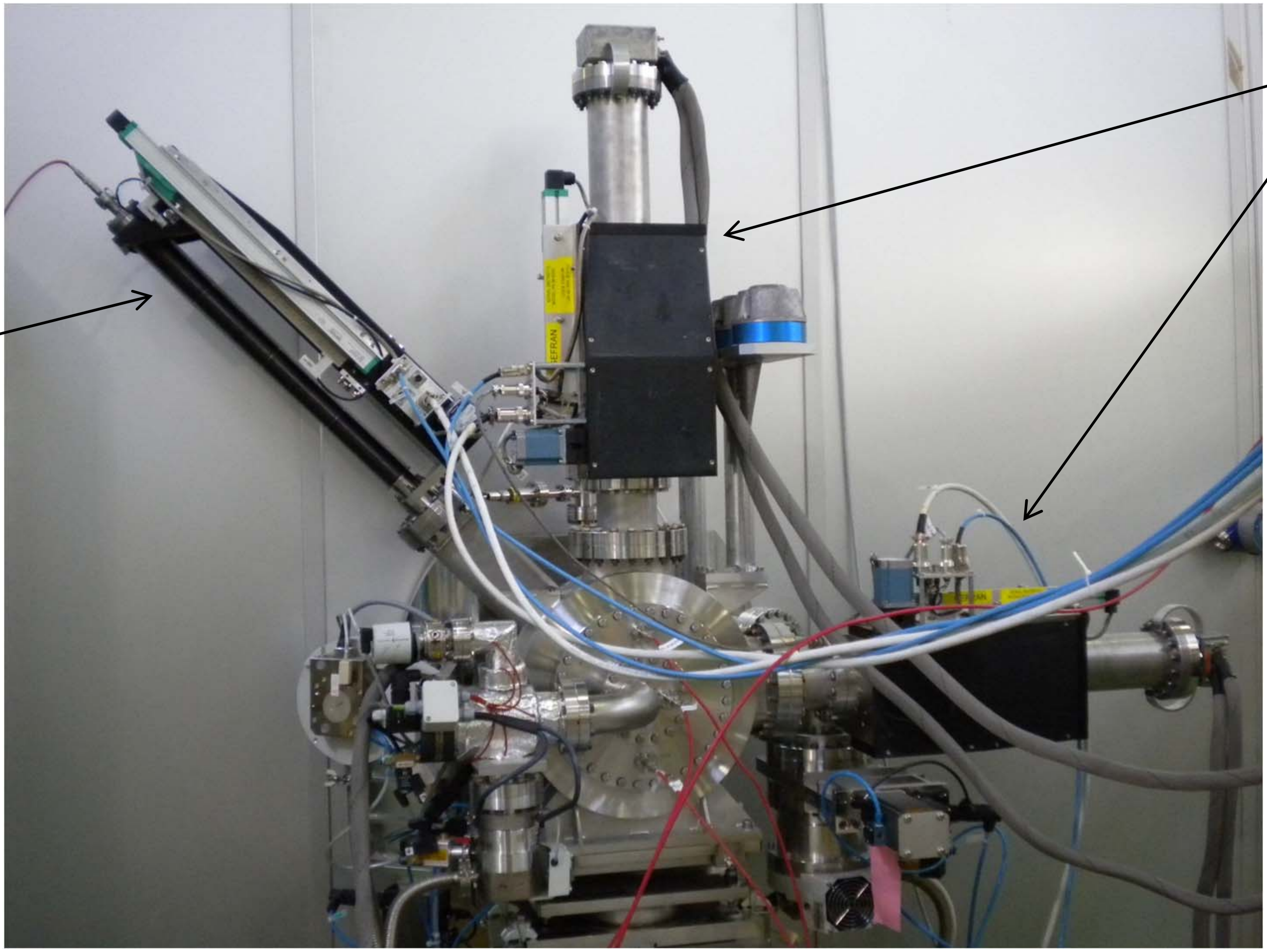
The Slit Method



Emittance Plot	
Entries	3488
Mean x	-1.465
Mean y	8.559
RMS x	9.807
RMS y	53.18



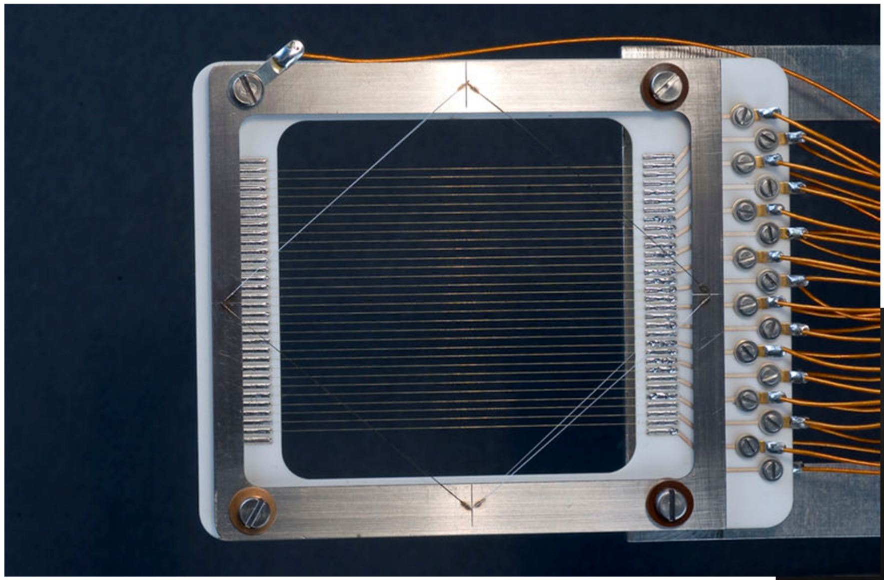
Transverse Emittance



hor and vert
wire grid

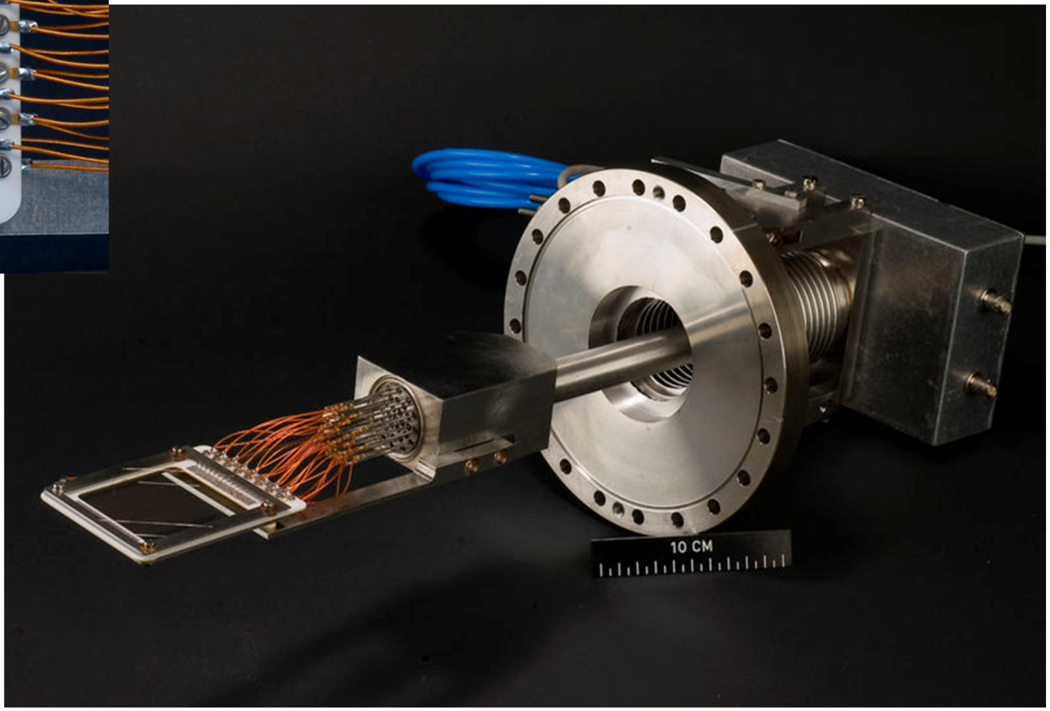
L-shaped slit

SEMGrid



Need different materials for the wire:

- Tungsten at higher energies
- Carbon at lower energies



Signal generation:

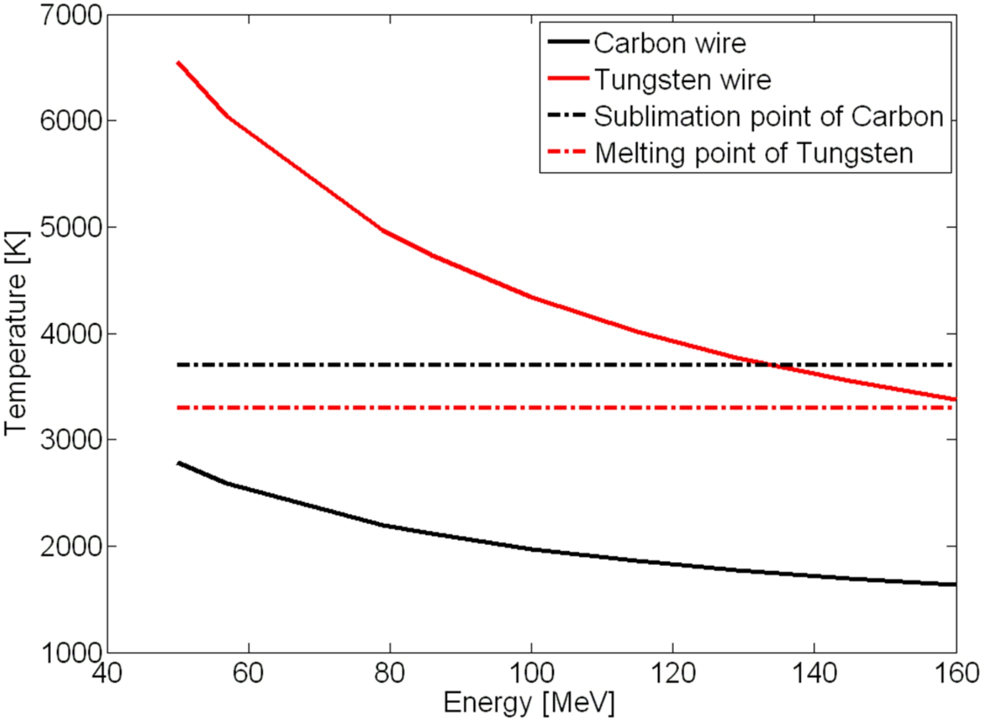
- secondary emission
- charge collection

depends on

- target material
- particle energy

SEMGrids

- Simulations of energy deposition
- Simulation of signal levels to be expected
- time resolved electronics (200 kHz
- Fabrication of grids with carbon wires

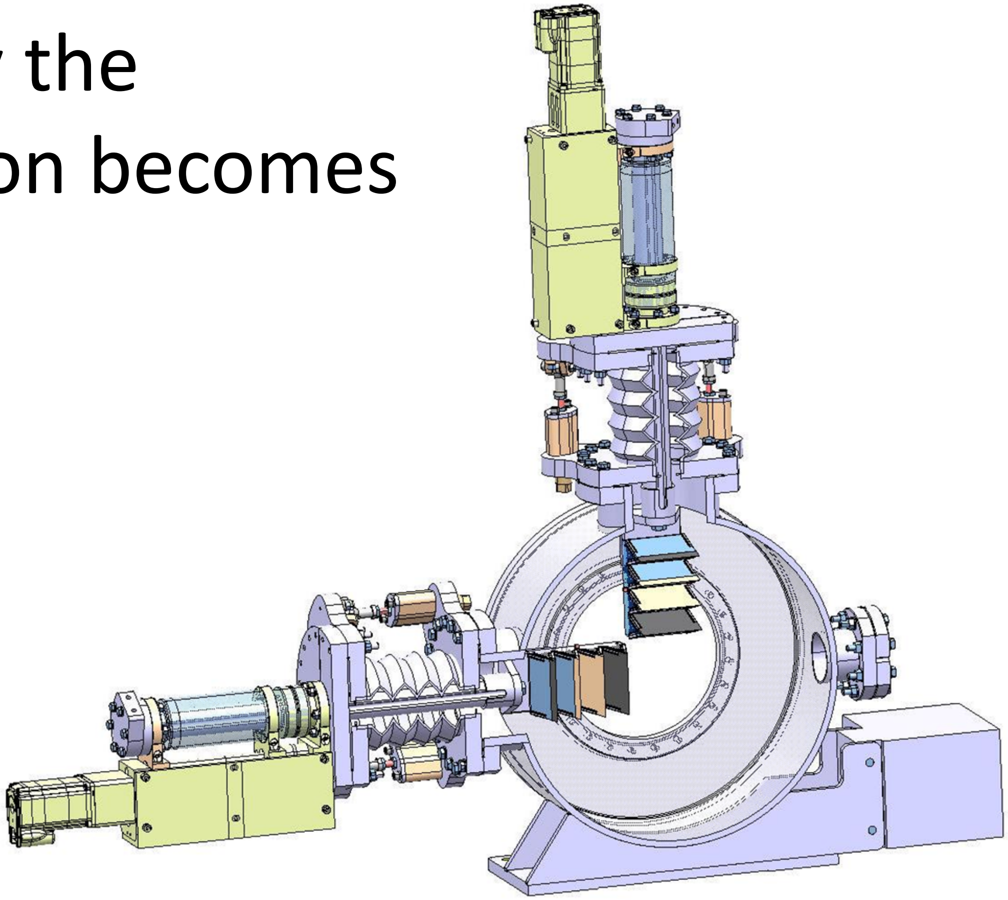


40 mA, 400 µs, σ_x=1mm, σ_y=2mm

Slit at 12 MeV

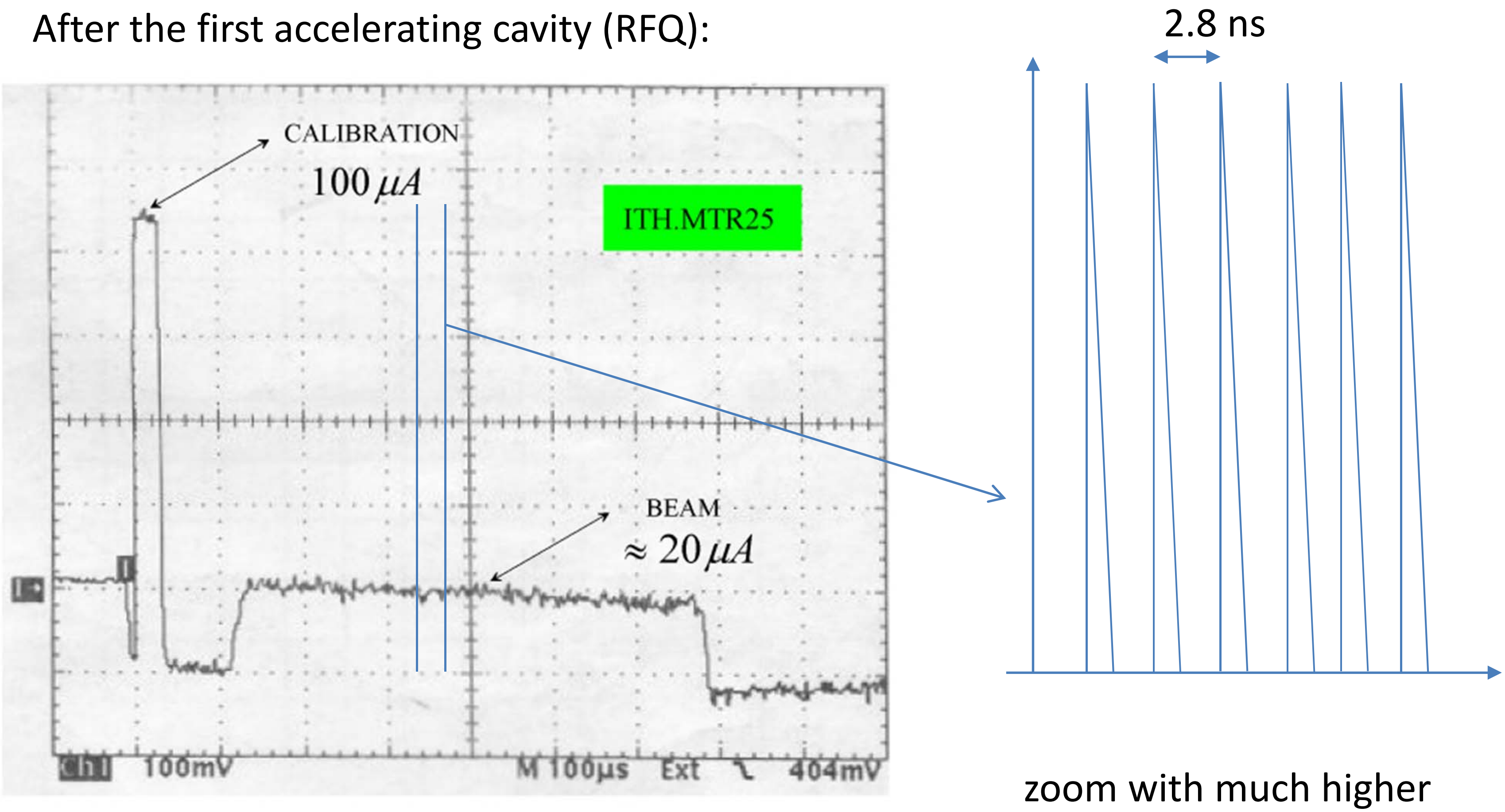
At higher particle energy the thermal energy deposition becomes critical:

- shorten pulse length4
- cooled slit design



Bunch shape measurements

After the first accelerating cavity (RFQ):



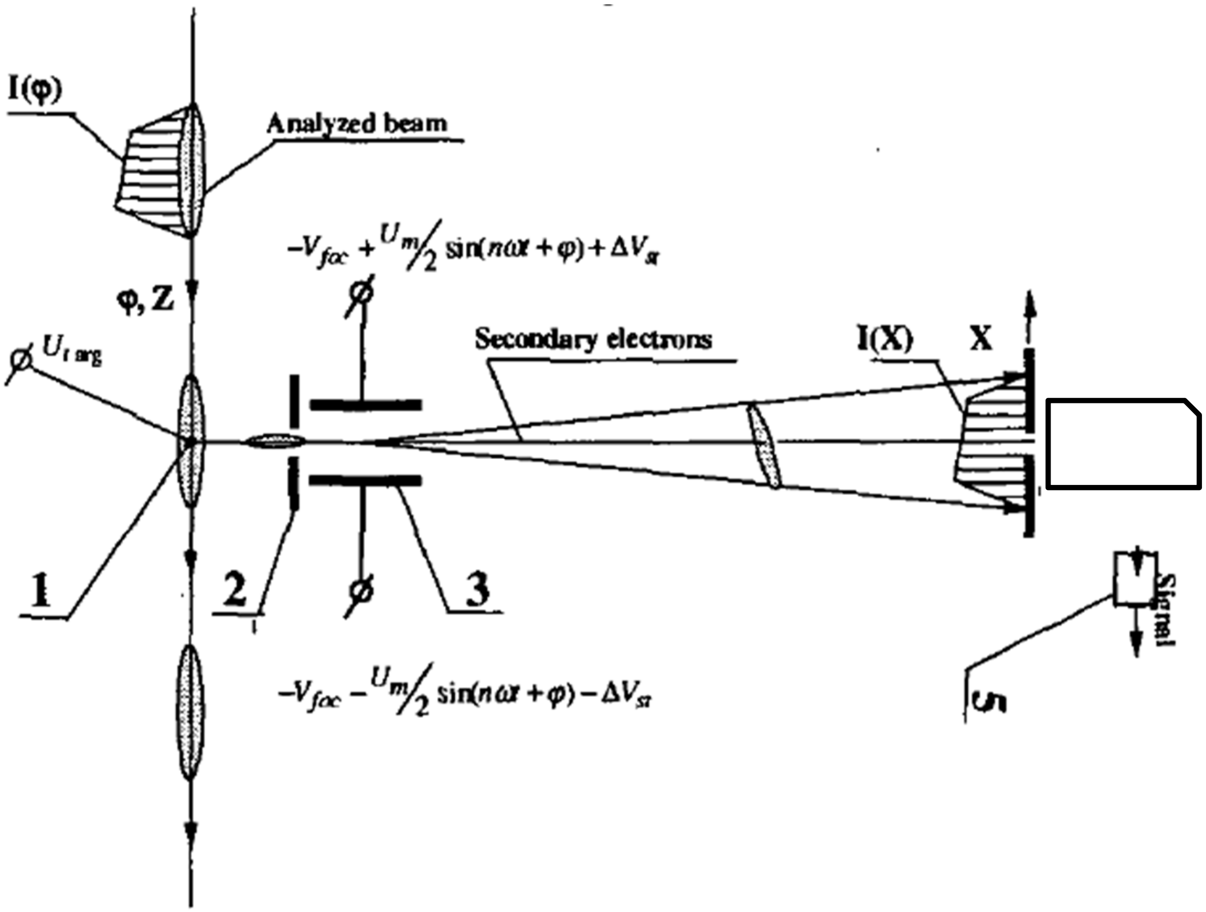
zoom with much higher bandwidth

Measuring the Bunch Shape

A very crude estimation:

- RF at 352 MHz -> RF-cycle: ~ 2.7 ns
- Bunch width ~ 20%: 540 ps
- want at least 20 points: resolution in the order of some ten ps

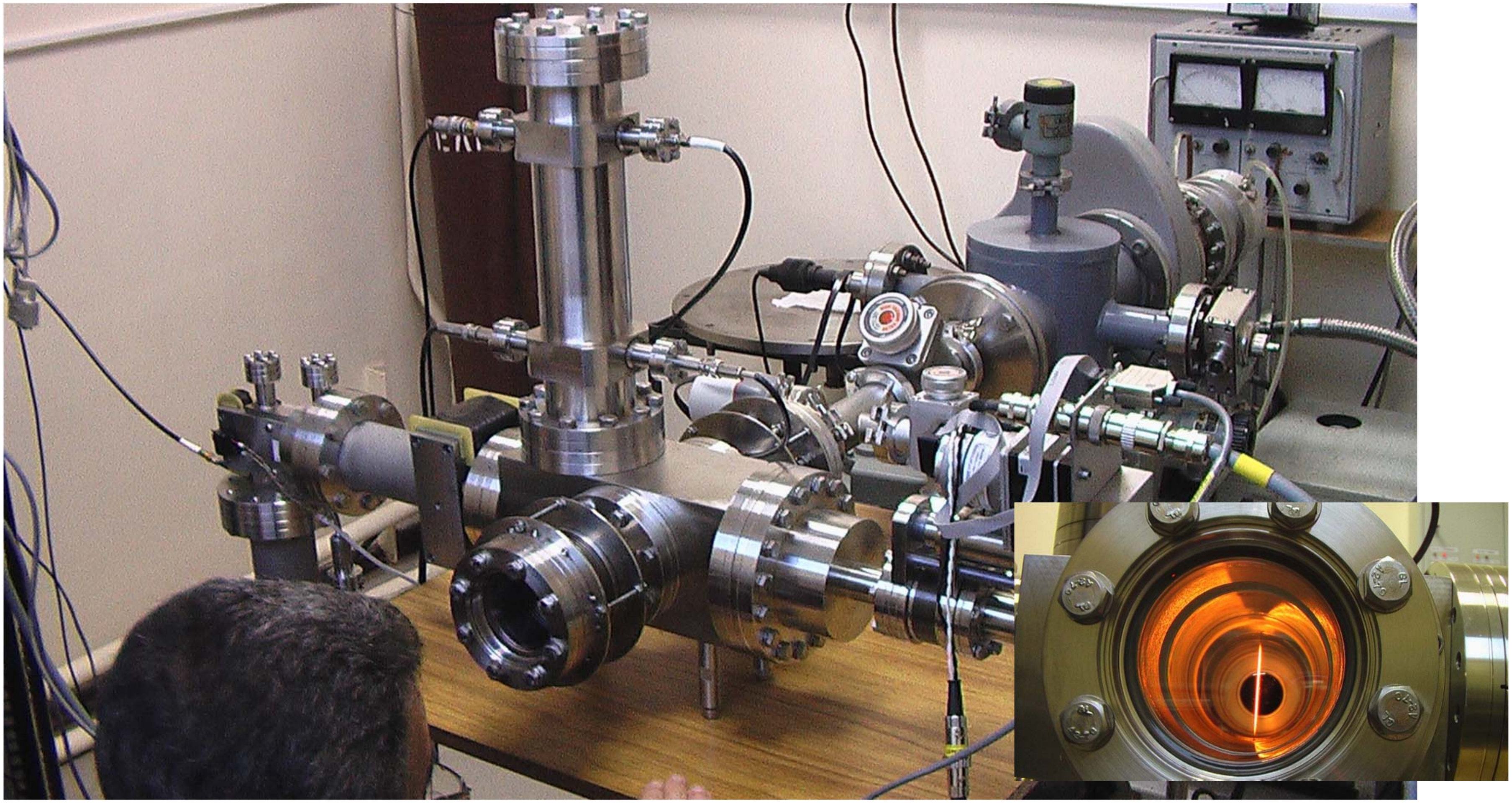
Principle of the BSM



Put a target wire into the beam (100 µm Tungsten wire).
Secondary electrons are created and accelerated due to HV on the target wire
The electrons pass through a slit followed by an RF deflector synchronous to the accelerator RF

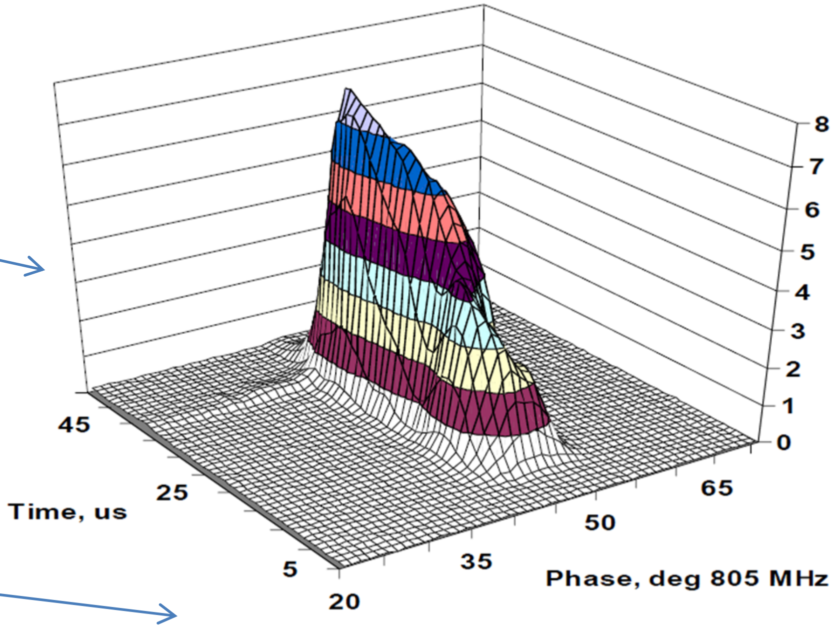
An electron detector detects particles with a defined phase
The deflector RF is shifted with a phase shifter

Photo of Linac-4 BSM



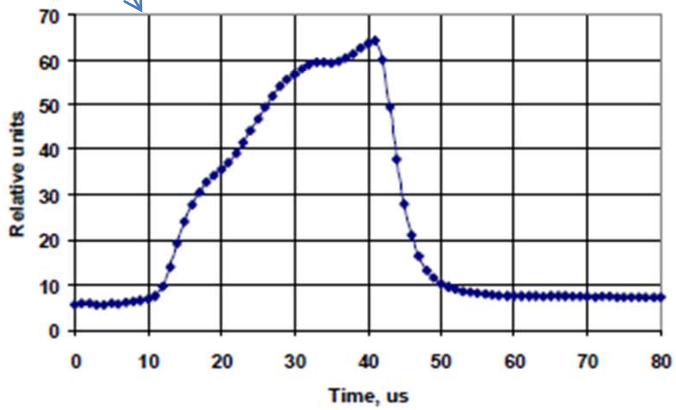
Typical BSM results

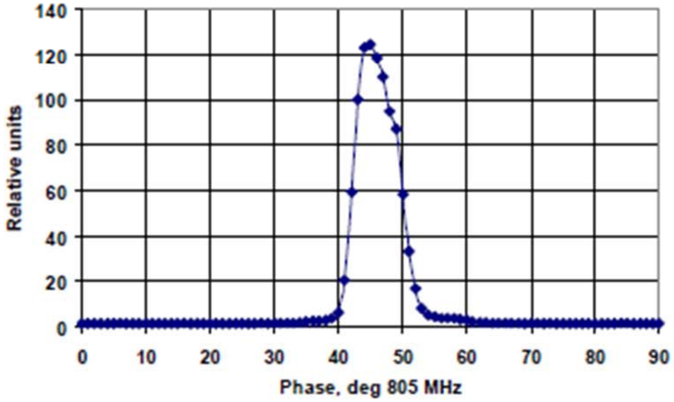
Typical BSM plot



Pulse shape

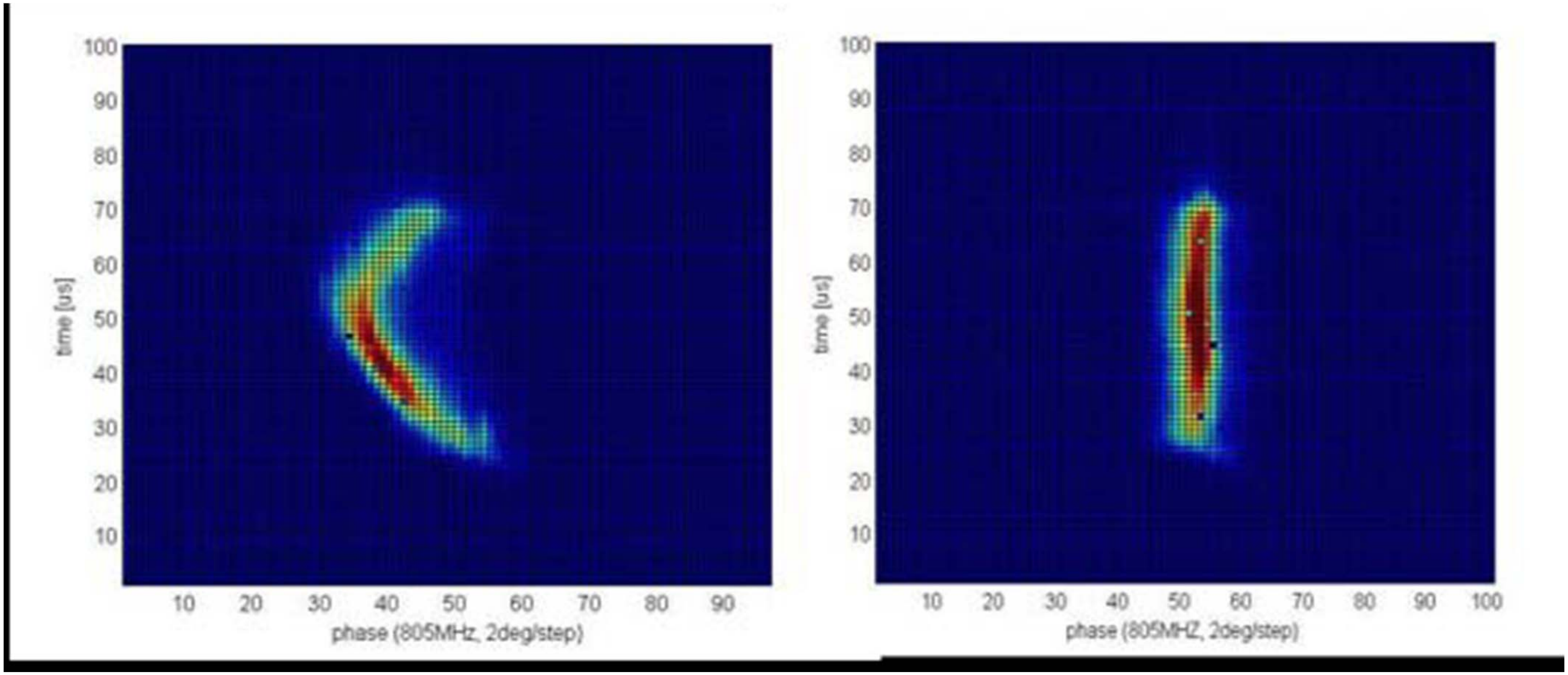
Longitidinal profile



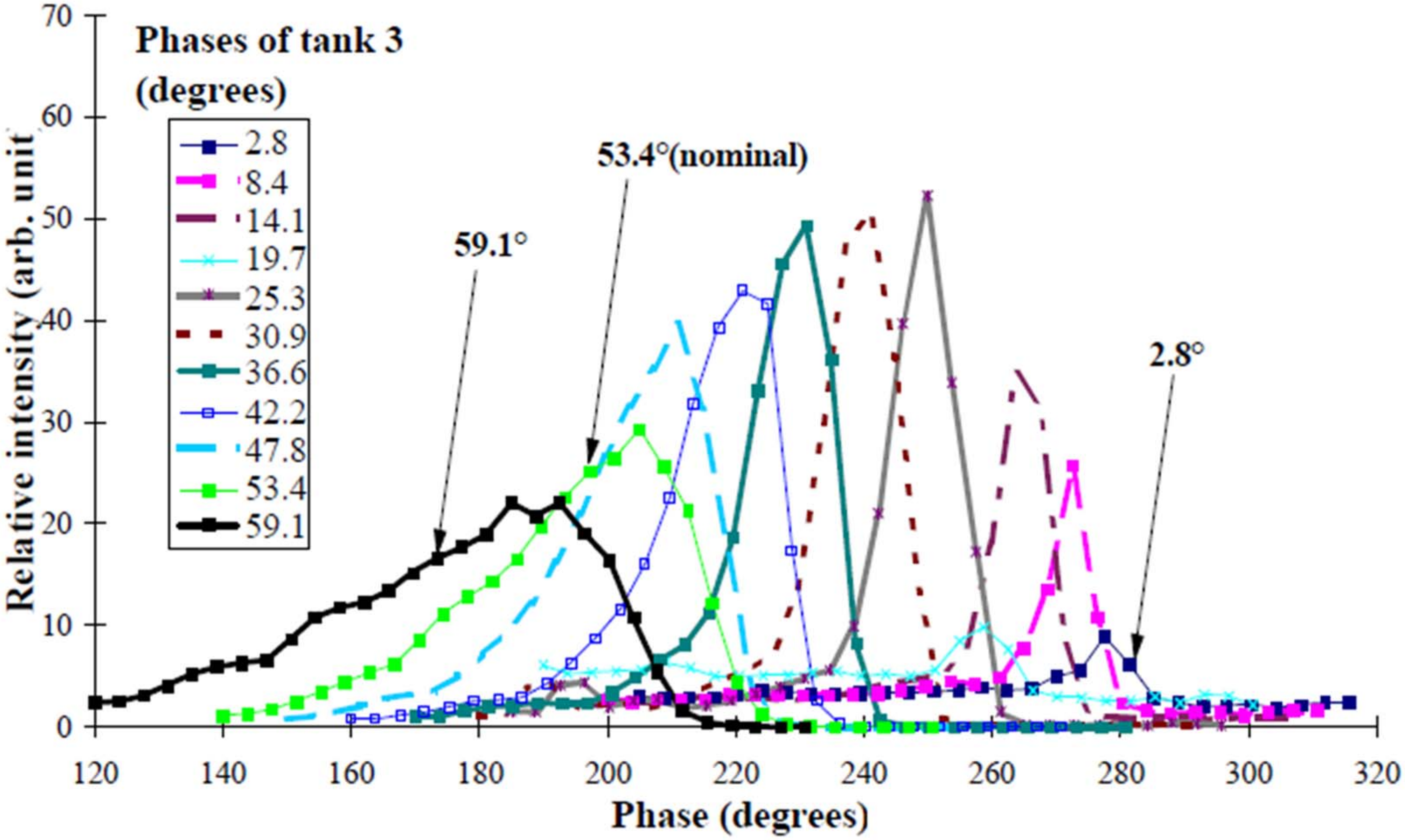


BSM results from SNS

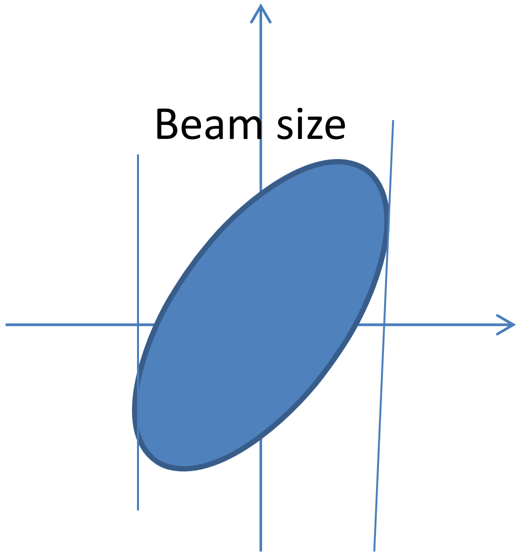
Bad beam loading compensation



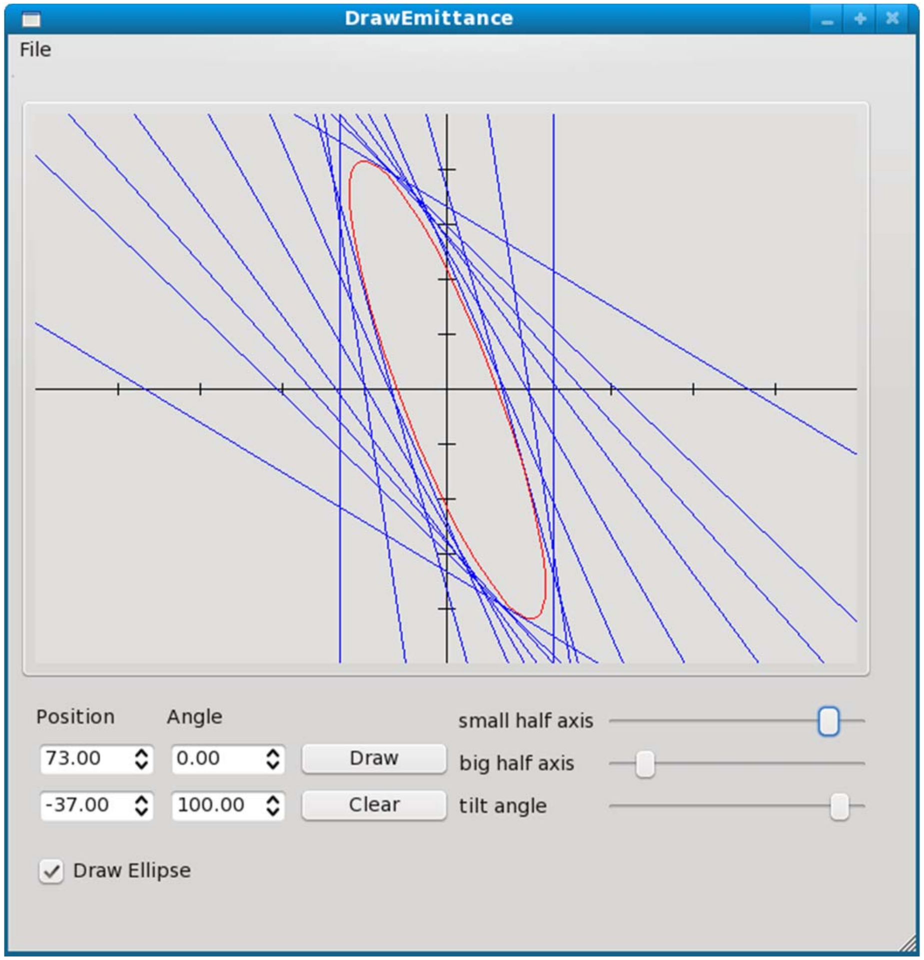
Adjusting RF phase



Multiple transverse Profile Measurements



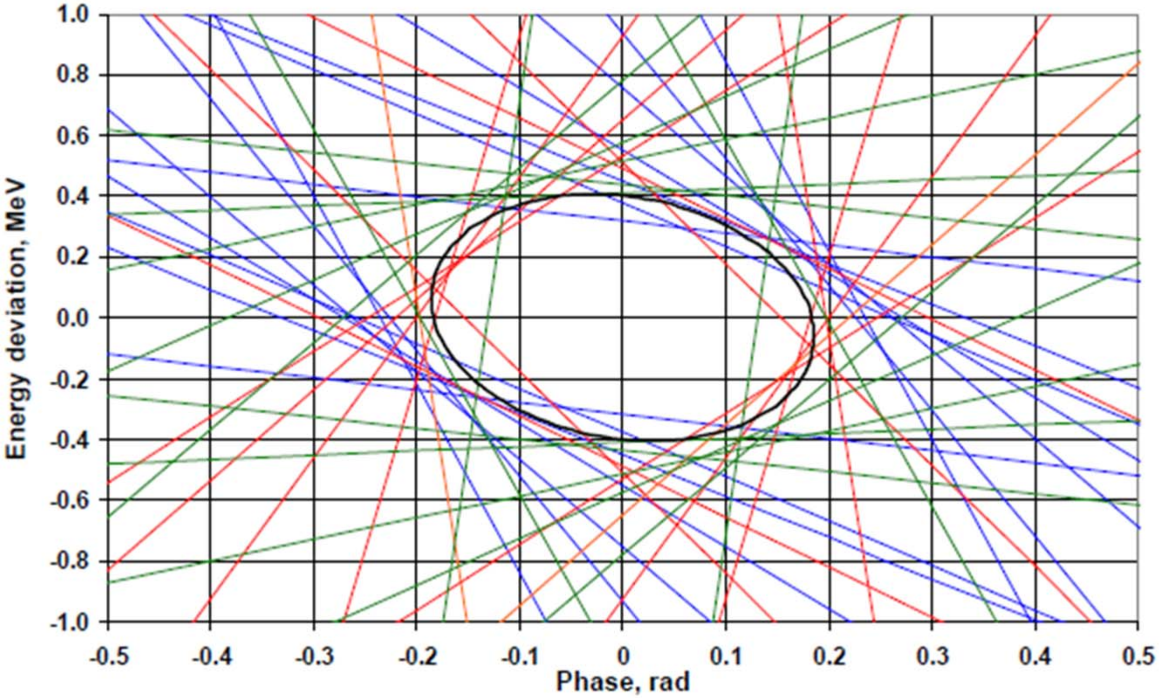
Measure beam size at several (min 3) locations
Using linear beasm optics
Transform all beam sizes to a single location



Position	Angle
73.00	0.00
-37.00	100.00

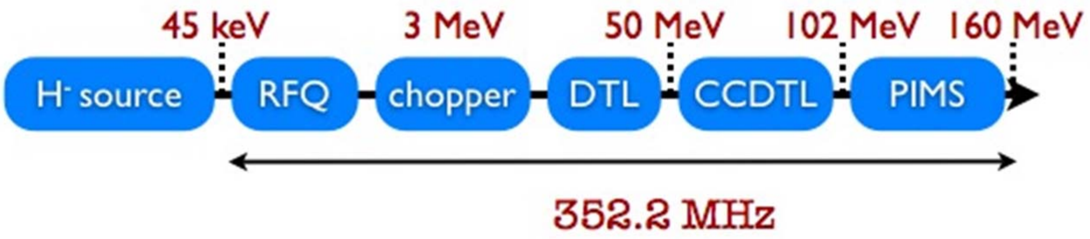
☑ Draw Ellipse

Longitudial emittance



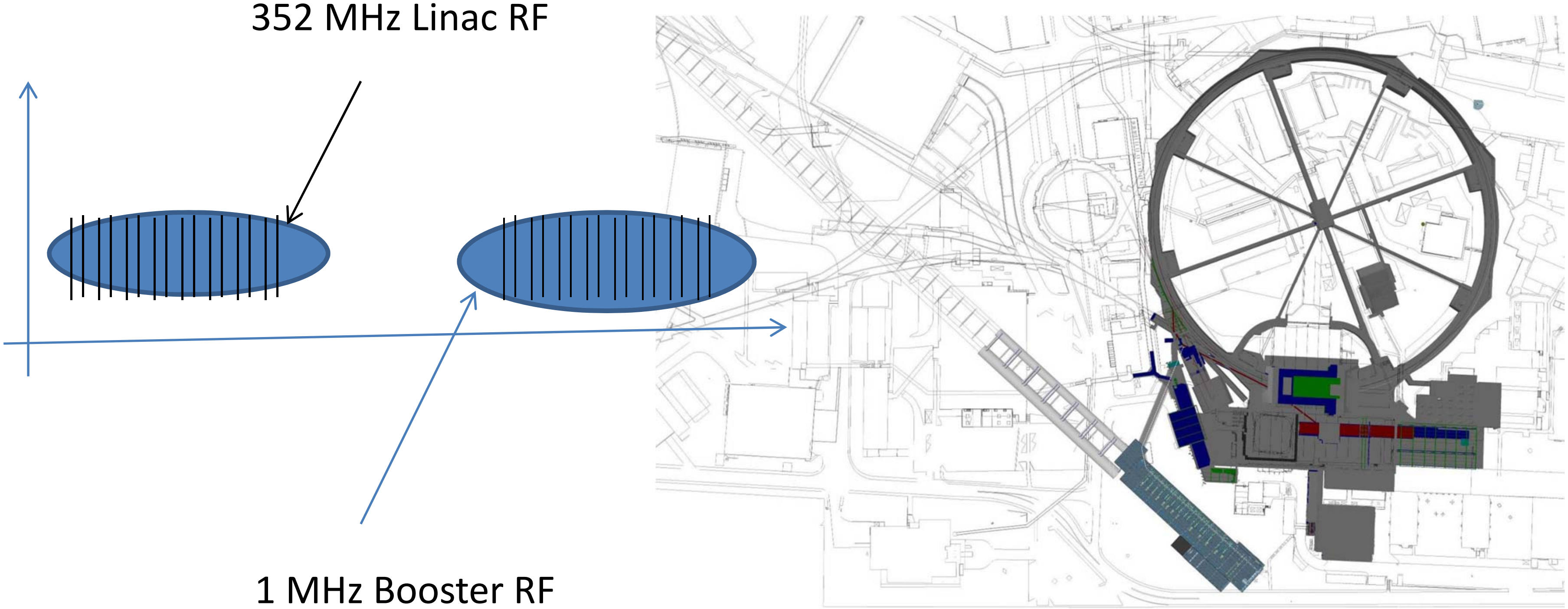
Bunch shape measured at 3 locations
RF amplitude was modified with corresponding phase correction

The chopper line



- “Longitudinal matching” from the LINAC (352 MHZ) to the booster frequency (1 MHZ) to avoid capture losses.
- Eliminate 133/352 linac micro-bunches at the lowest possible energy (3MeV)
- Combination of fast rise-time and high voltage is difficult and therefore the chopper is a LONG object compared to the characteristic FODO length at 3 MeV and 352 MHZ (~ 7 cm)
- Design which includes quadrupoles to amplify the chopper kick and it’s as close as possible to FODO to minimze emitance growth

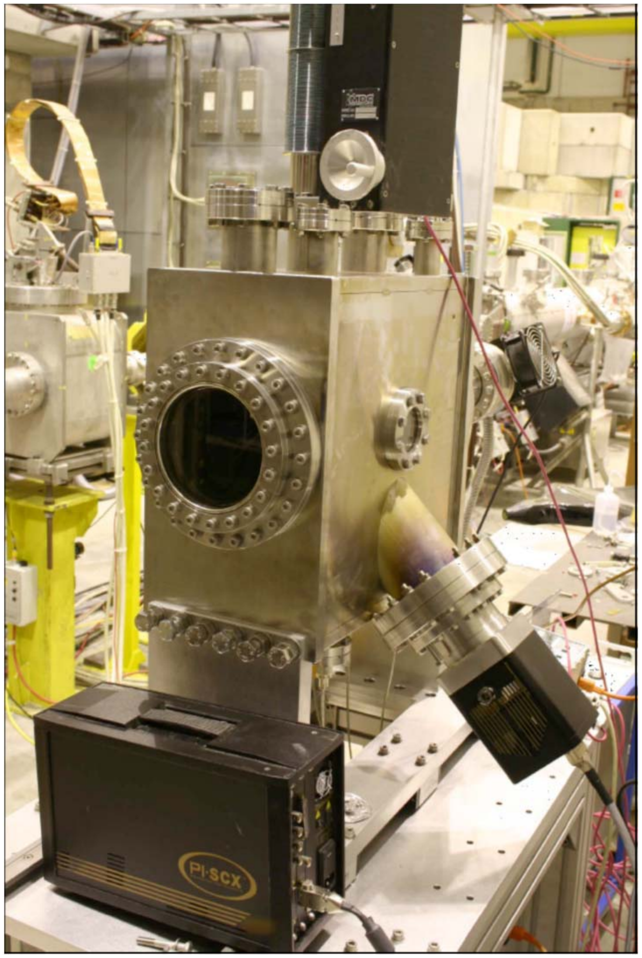
Transfer of beam into the Booster

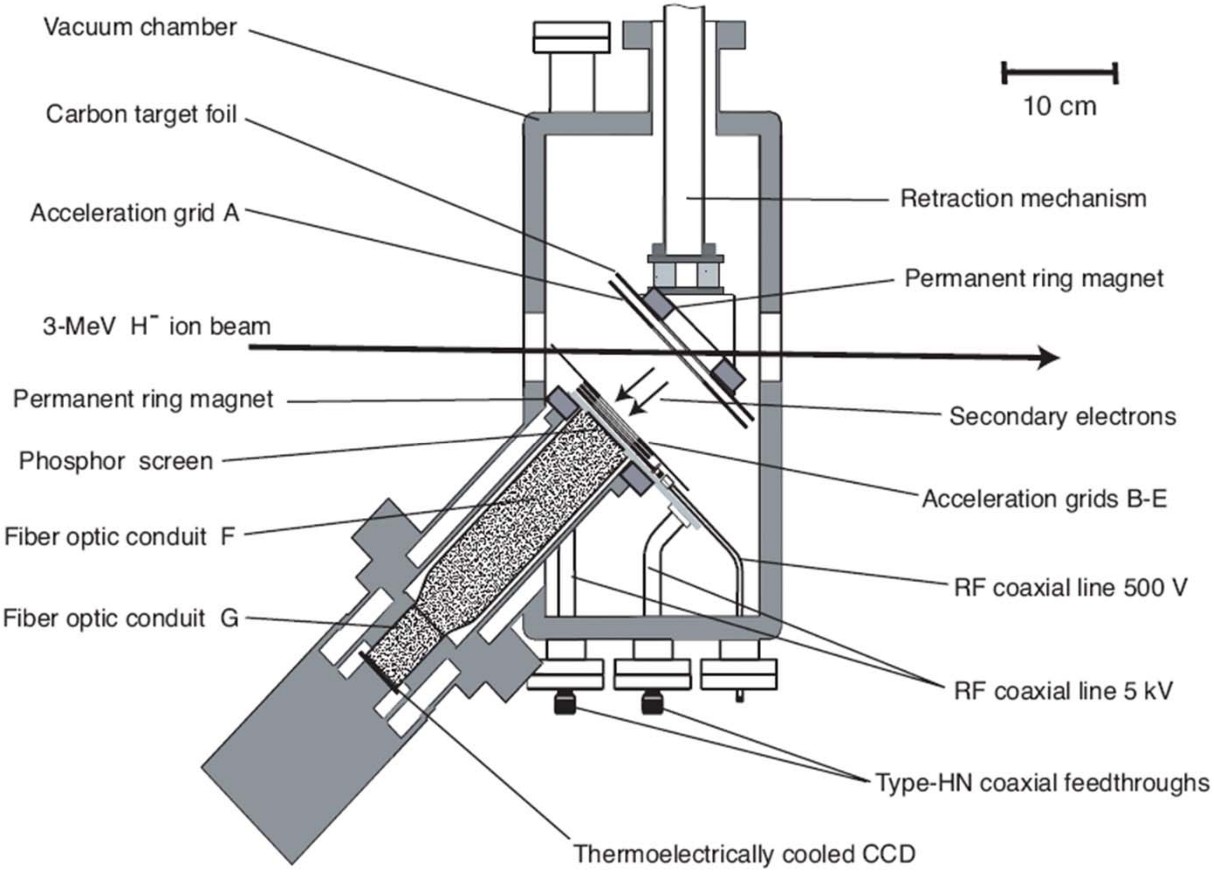


352 MHz Linac RF

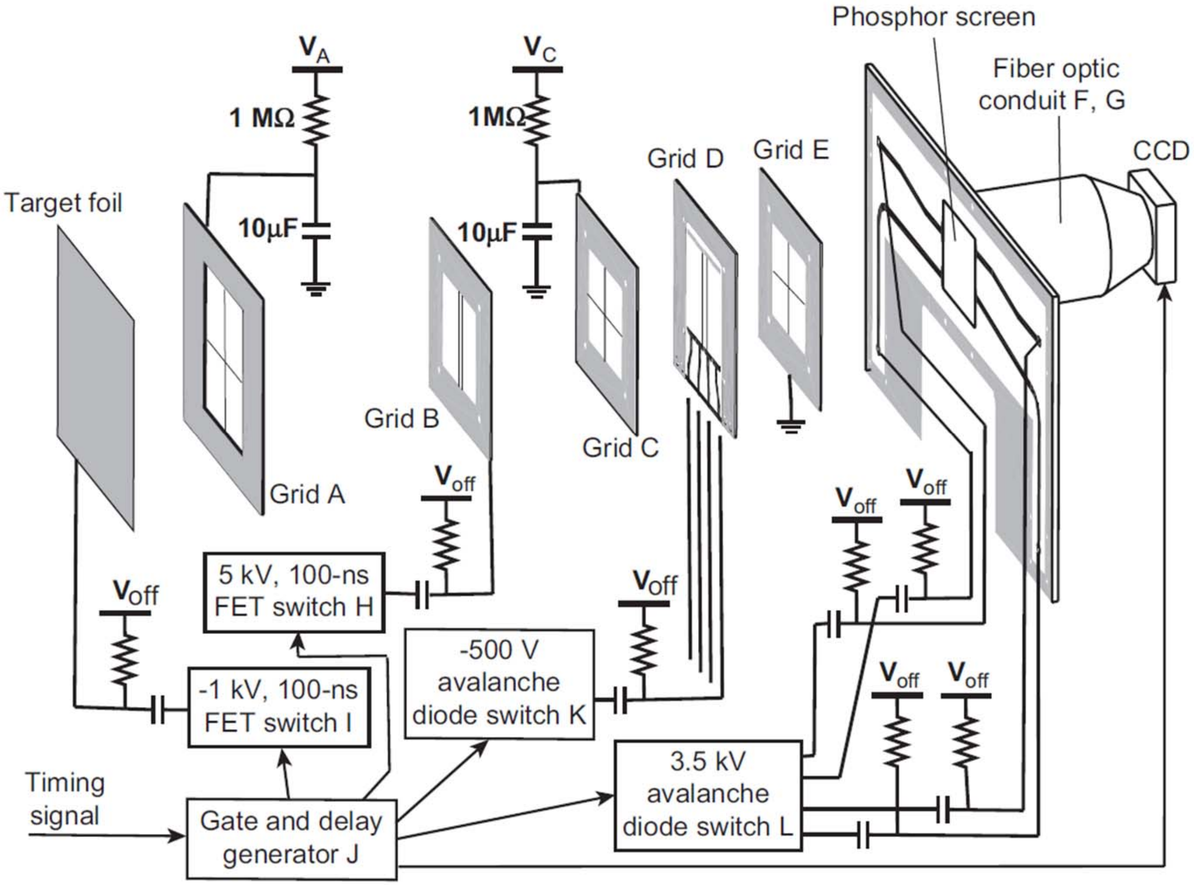
1 MHz Booster RF

Halo Monitor





Generating very short gates



Gated off:

- 0.8 kV on foil, -0.3kV on GB

Accelerate but don‘t penetrate the phosphor

- -0.2 kV on foil (100 ns pulse)

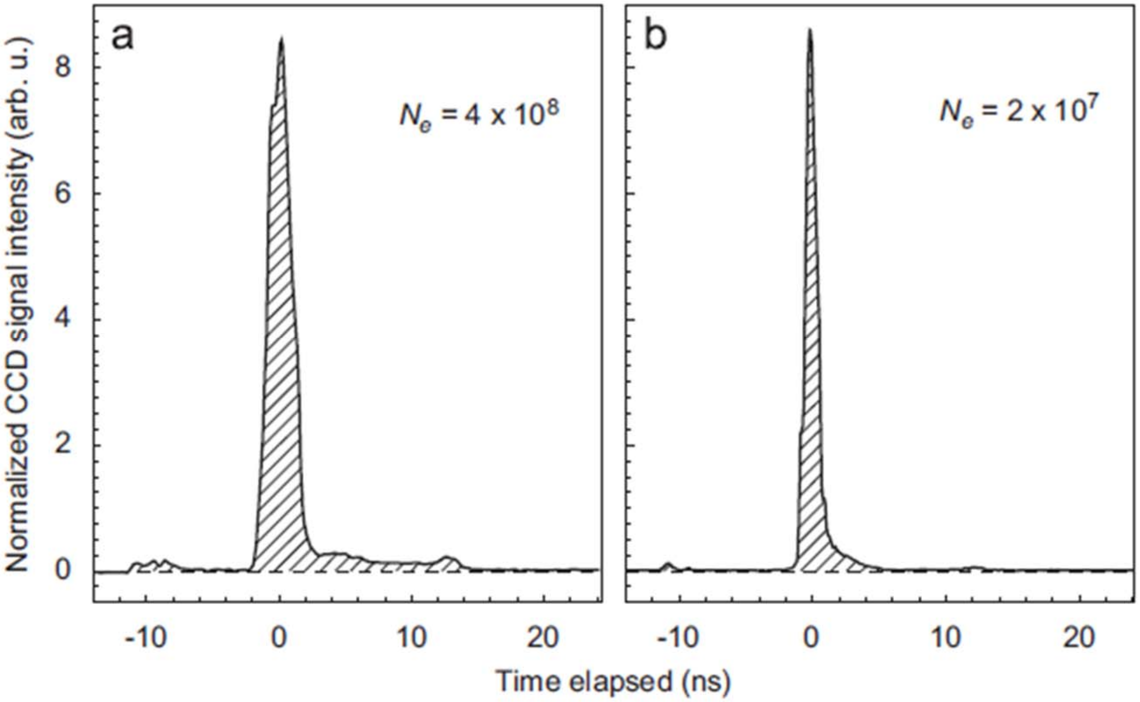
Flourescence on:

- 3.5 kV pulse 200 ps rise time reflection doubles the pulse to ~ 6 kV

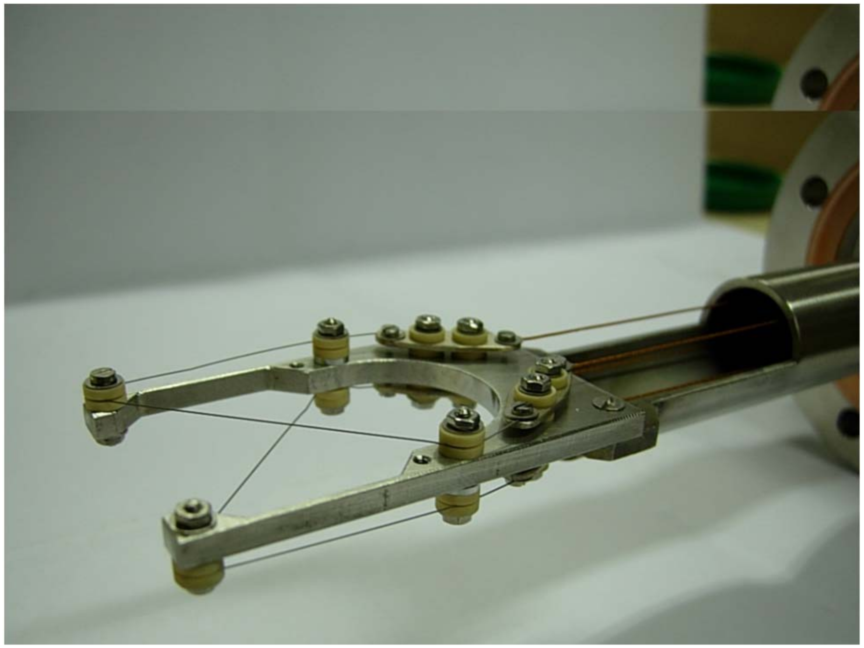
Flourescence off:

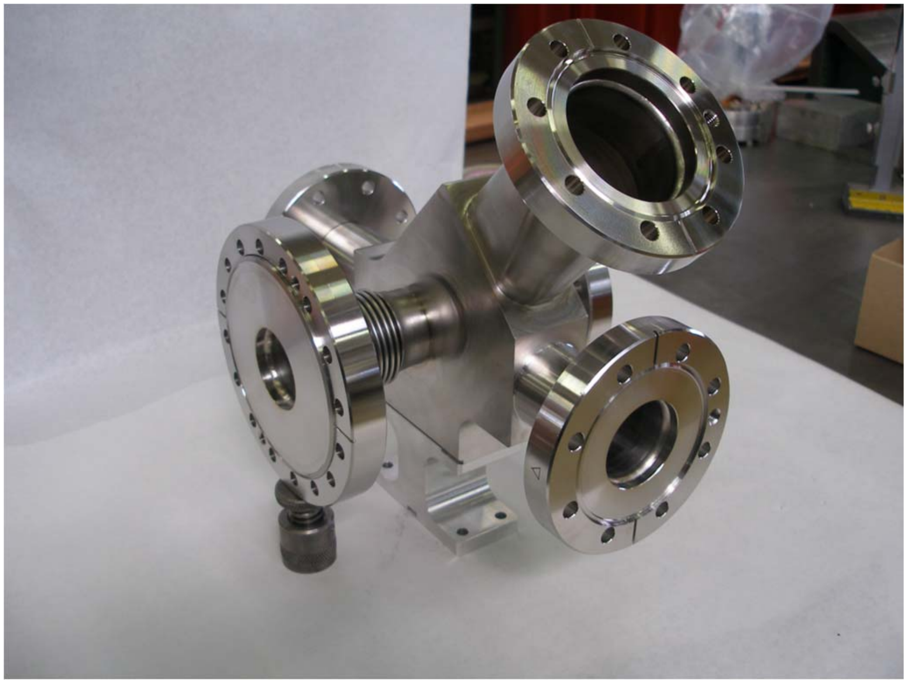
- -500V pulse again doubled to

Test Results from Halo Monitor



Wire Scanner



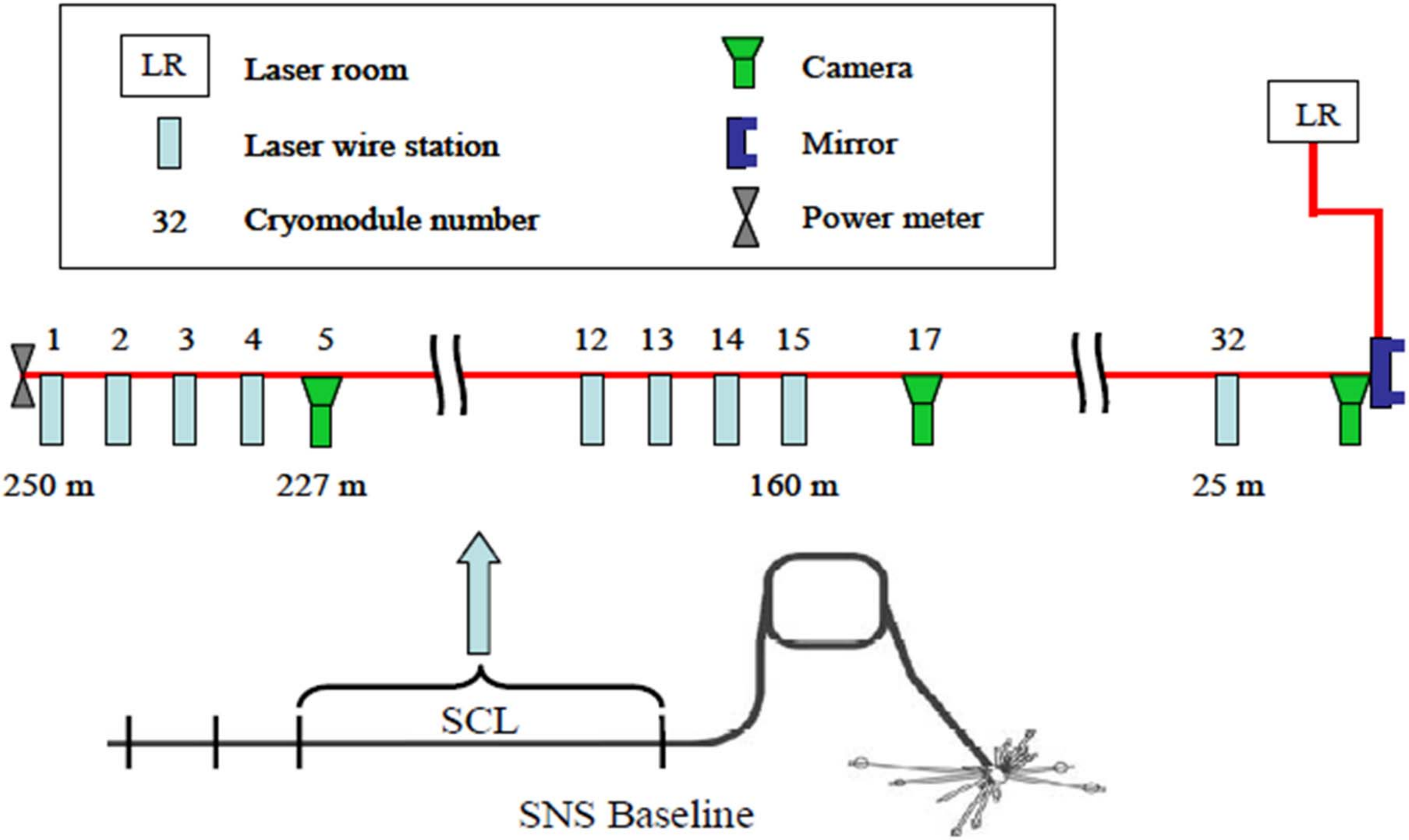


Problems:
- Interceptive, causes losses
- Cannot stand full pulse length

On H^- beams: photo detachment

- A thin laser beam traverses the beam
- The supplementary electron is detached leaving H^0
- Detection of detached electrons allows to measure profile
- May act like a slit
- Usings a bending magnet a slit / grid emittance measurement may be possible

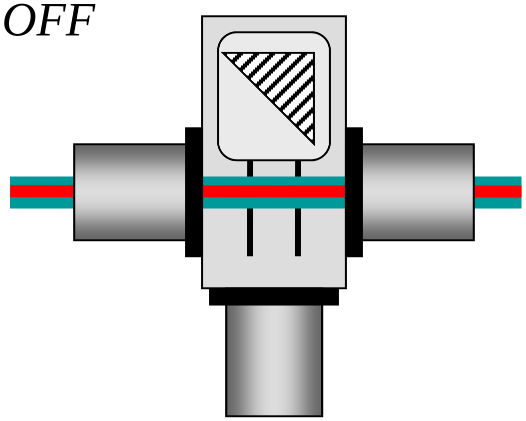
Laser Wire System at SNS



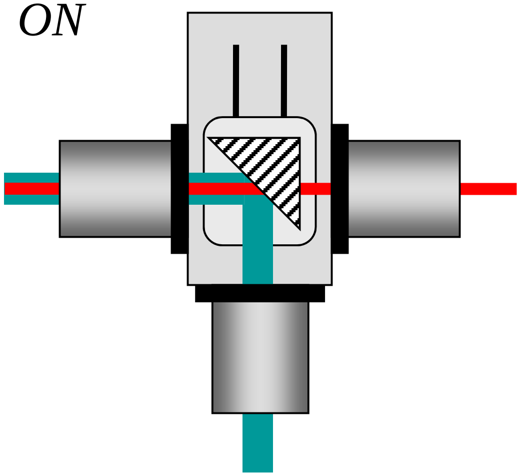
Laser beam pick-offs

The beam is diverted from the main line by a pneumatically driven stage.

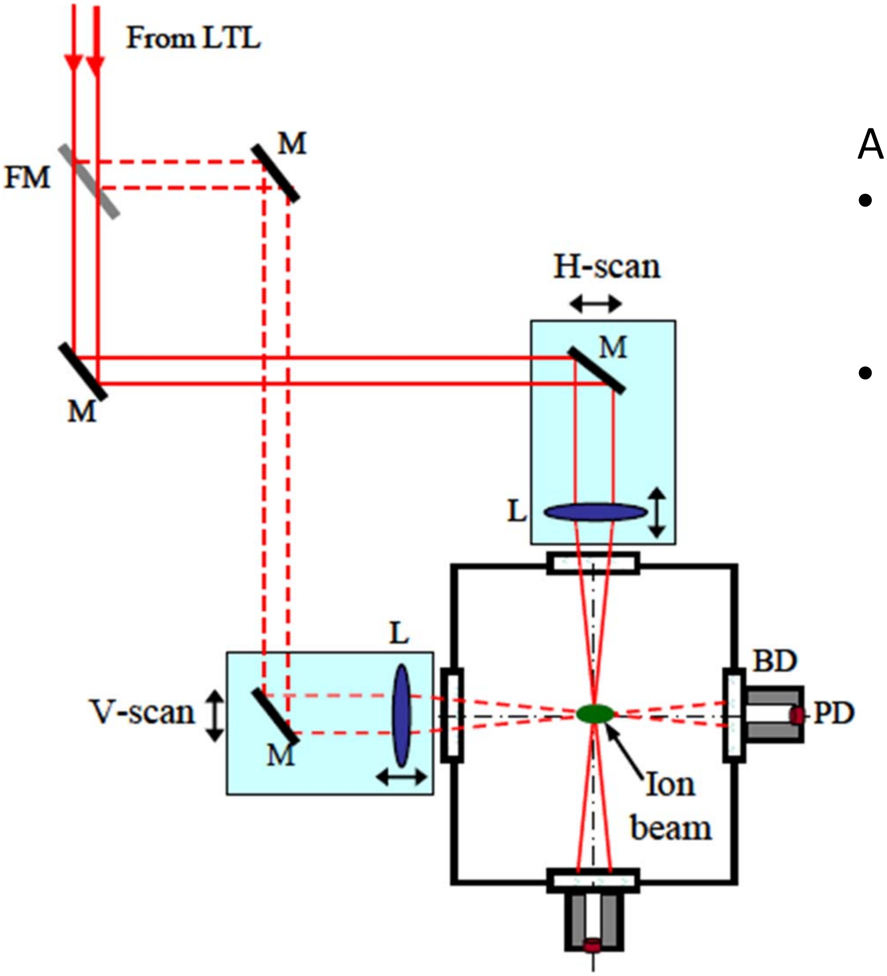
OFF



ON



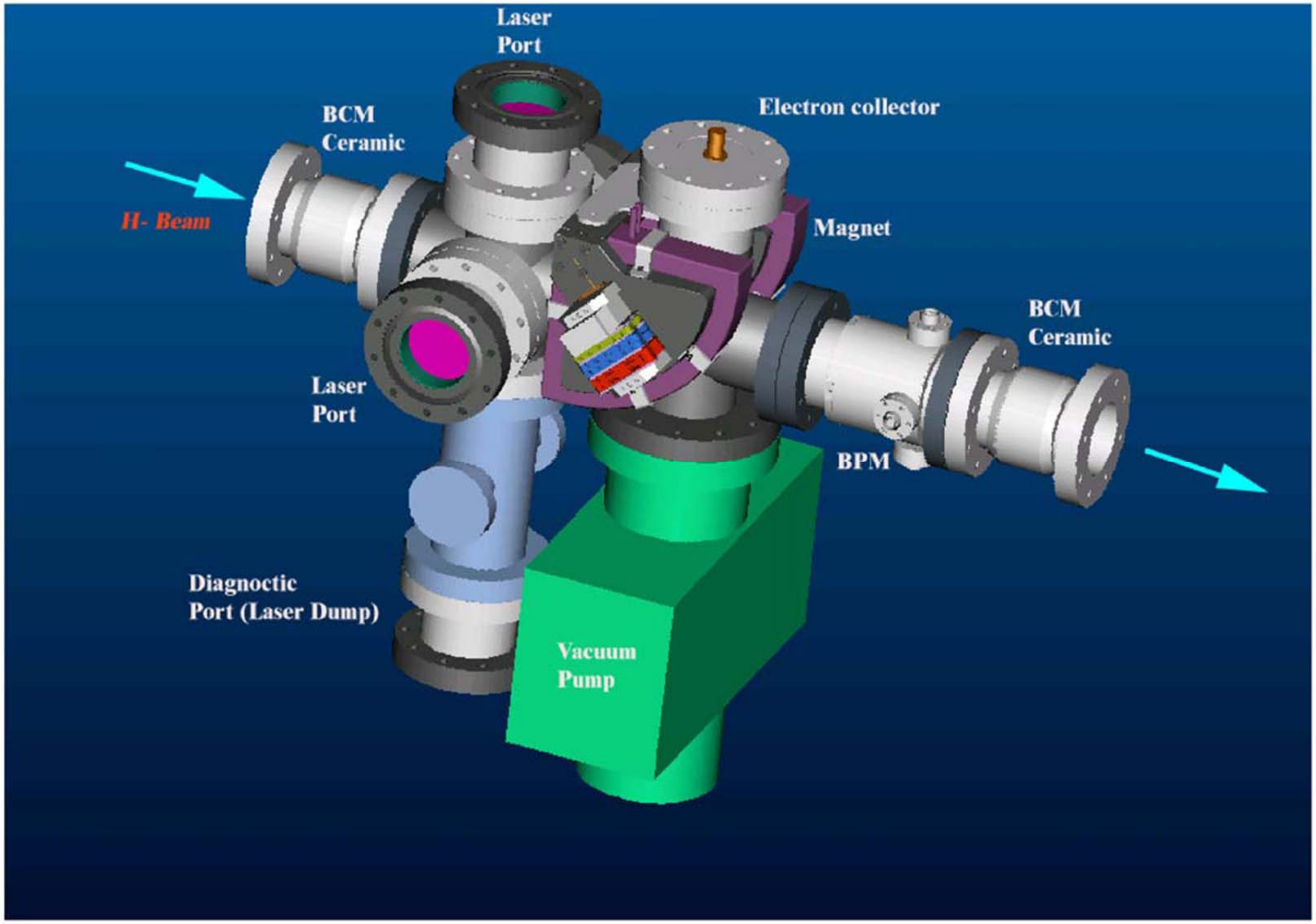
Layout of SNS Laser Station



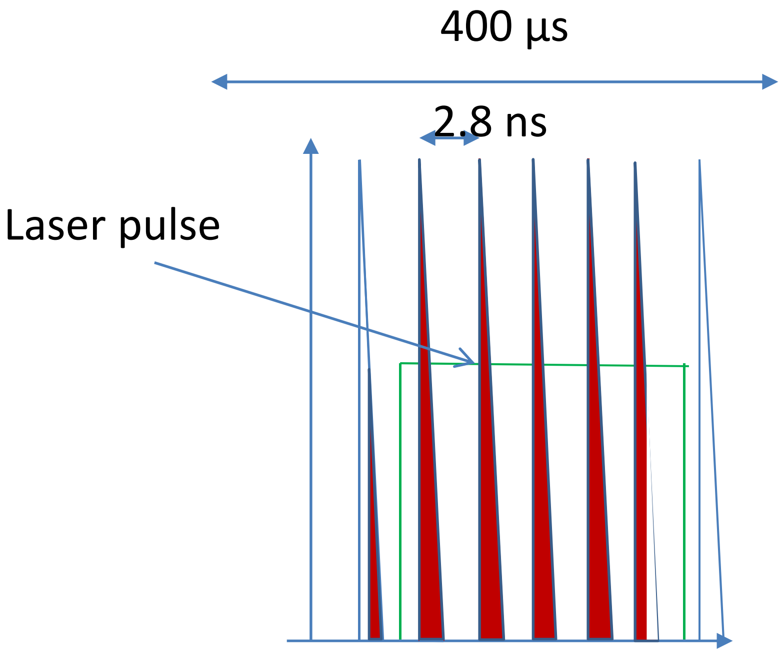
Advantages of Laser Wire:

- No intercepting material especially important for supra conducting cavities
- Not disturbing the beam
  10 ns laser pulse out of ~1 ms

SNS Laser Station



Precision of Laser Wire

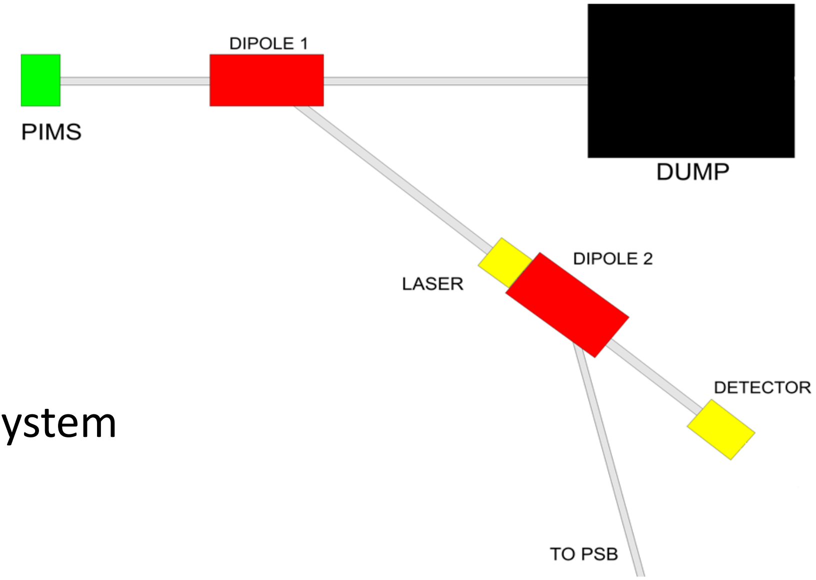


Precise synchronization between micro bunches and laser pulse

Determination of laser position

Emittance Measurement with Laser Wire

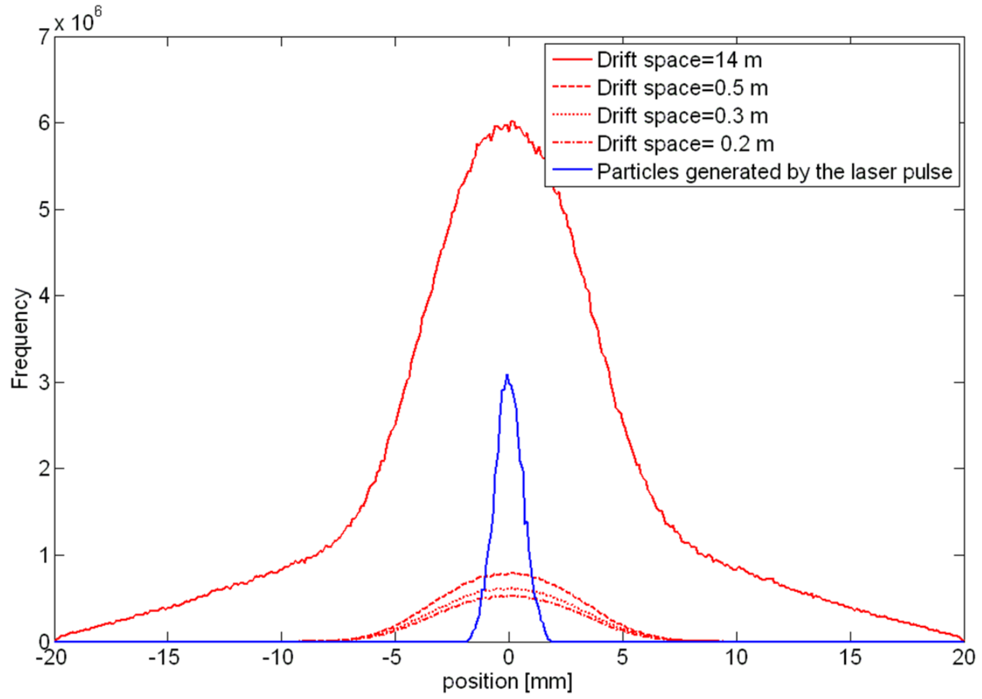
- During the acceleration along the linac and the travel between the end of the linac and the PS booster, the second electron can be stripped from black body radiation, magnetic field and residual gas.
- A part of this neutral beam can reach the H0 detector and perturb the measurement.
- Simulations has been done to estimate the background



Layout of the system

Background issues

- With a laser system similar to SNS and laser beam size of 100 µm and assuming a full stripping the number of stripped particles is around 10^7



Particles reaching a detector positioned 2 m downstream the dipole.

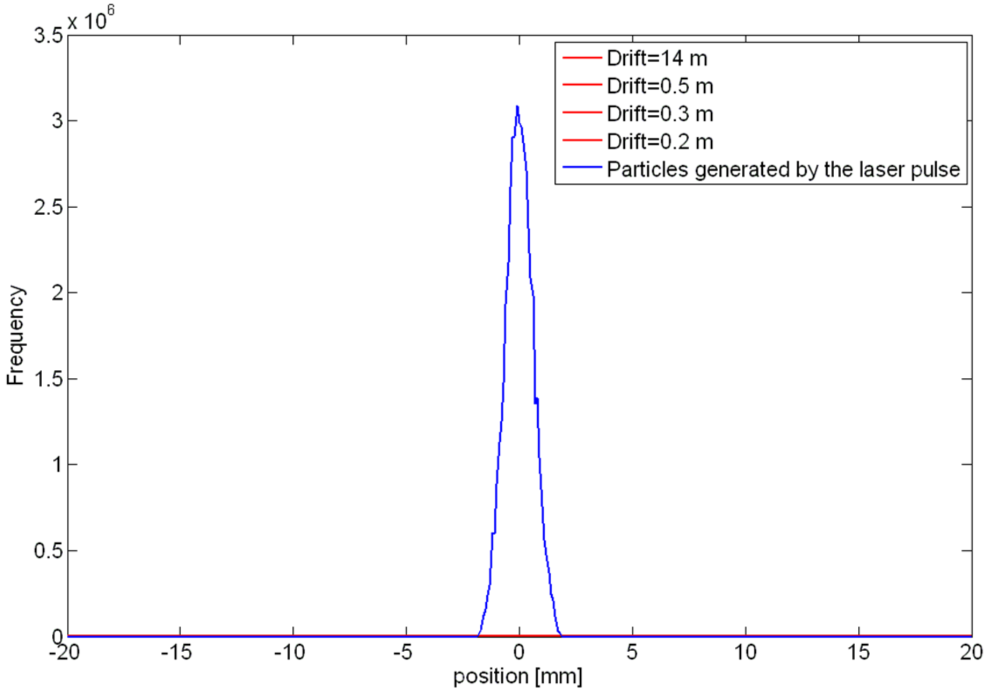
Drift length [m]	Nunber of particles
14	6.87E+08
0.5	5.80E+07
0.3	4.59E+07
0.2	3.94E+07

Number of background particles reaching the detector

If the signal is integrated over the linac pulse, the number of the background particles is in the order of magnitude of the signal in the better case.

Background issues

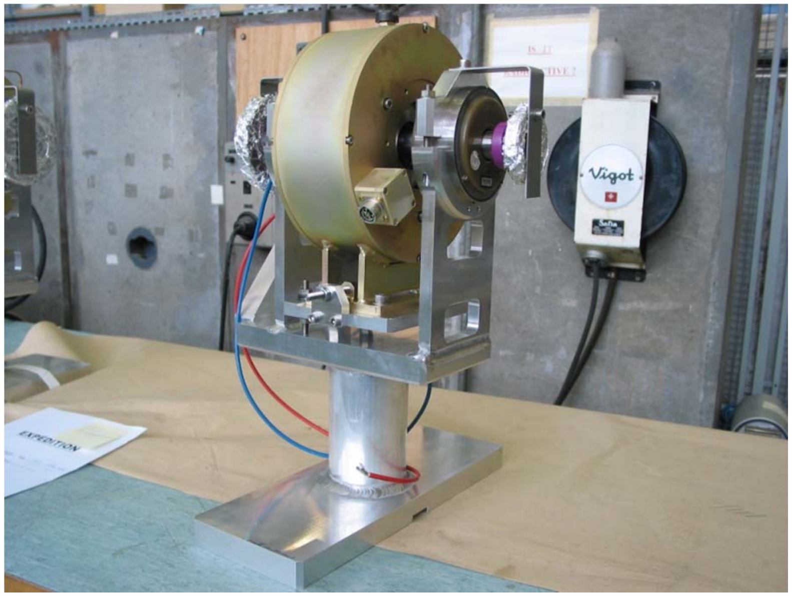
- If we assume that the probability of stripping by residual gas interaction or magnetic field stripping is independent of time, the background particles are generated over a pulse, i.e 400 µs. For the signal, the particles are generated over a laser pulse, i.e. 10 ns.
- By gating the signal with a short time window, the background effect can be reduced. Assuming a window of 20 ns, the number of background particles can be reduce by a factor 20000



Drift length [m]	Nunber of particles
14	3.44E+04
0.5	2.90E+03
0.3	2.30E+03
0.2	1.97E+03

Beam Losses

- Beam losses must be kept lower than 1W/m
- Loss of not more than a single beam pulse is allowed
- Use (hardware) comparison of transformer readings

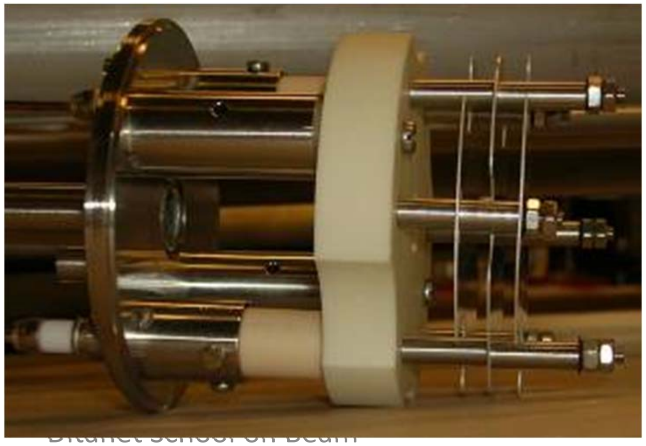


Beam Loss Monitor Types

- Design criteria: Signal speed and robustness
- Dynamic range (> 10^9) limited by leakage current through insulator ceramics (lower) and saturation due to space charge (upper limit).

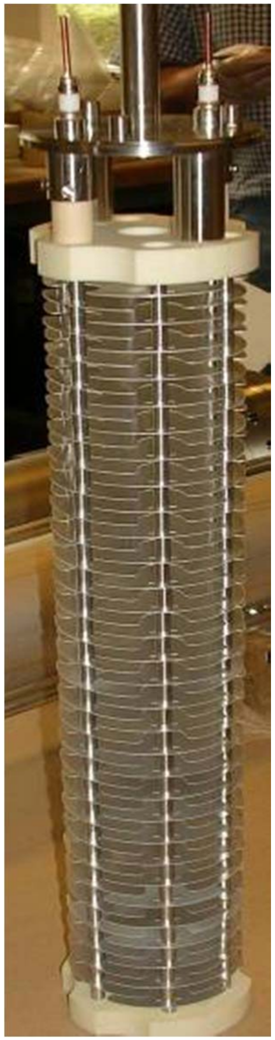
Secondary Emission Monitor (SEM):

- Length 10 cm
- P < 10^{-7} bar
- ~ 30000 times smaller gain



Ionization chamber:

- N_2 gas filling at 100 mbar over-pressure
- Length 50 cm
- Sensitive volume 1.5 l
- Ion collection time 85 μs



- Both monitors:
  - Parallel electrodes (Al, SEM: Ti) separated by 0.5 cm
  - Low pass filter at the HV input
  - Voltage 1.5 kV

Acknowledgements

- Transparencies from
  M. Hori & K. Hanke (Halo Monitor)
  Laser Wire SNS team
  Emittance user Laser Wire: B. Cheymol
  BSM: A Feshenko + INR team
  Linac-4 team