Beam Instrumentation for High Power Hadron Beams

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Types of accelerators discussed

- Average beam power: ~ 1 MW
- Beam energy: ~ 1 GeV
  - Non-relativistic beam
- Beam species: protons, H, heavy ions
- Time structure: pulsed or CW
- Examples: SNS, PSI, J-PARC, FRIB, Project-X, ESS …

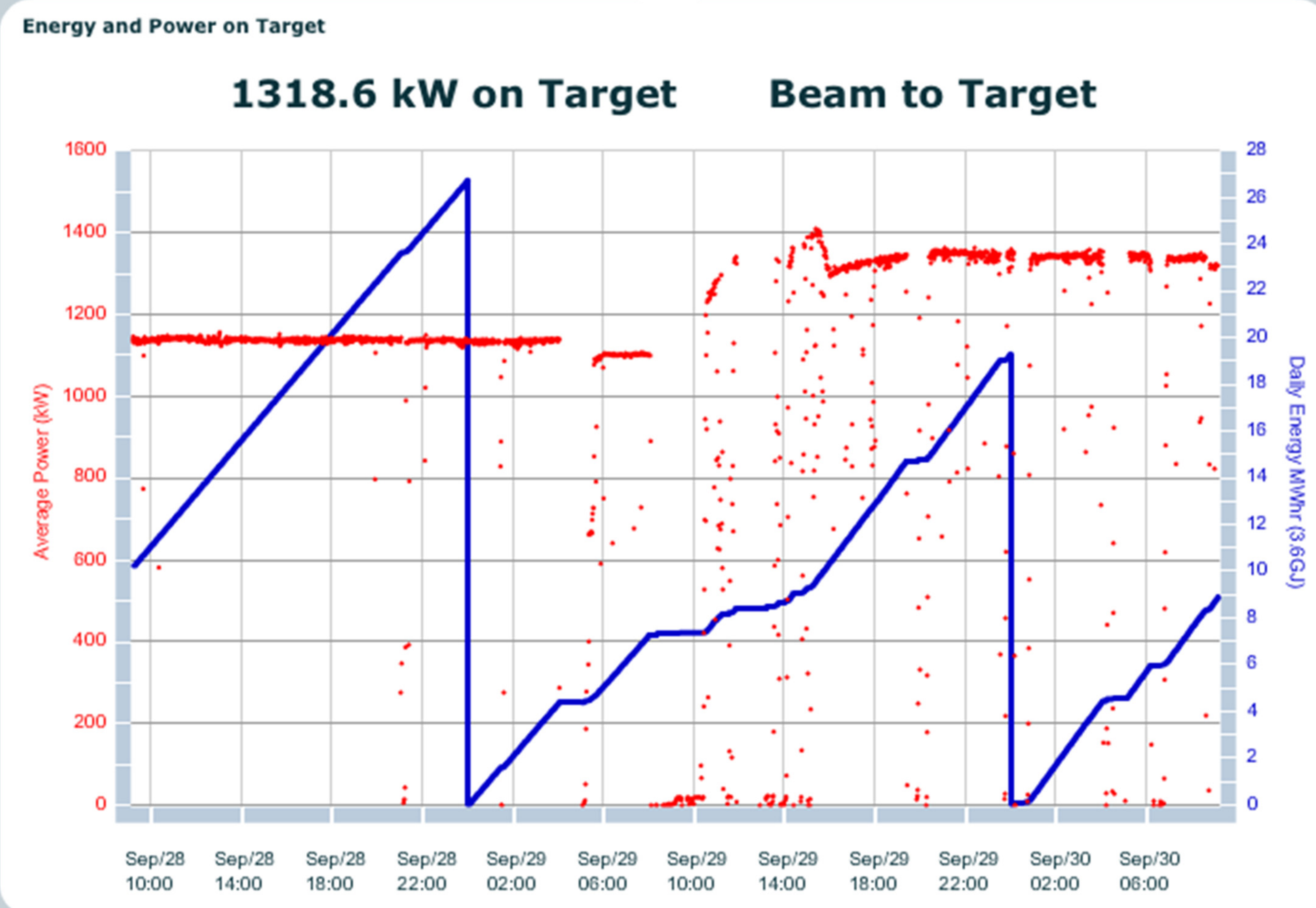
- Typical beam size: 1-10 mm
- Typical bunch length: 1- 100 ps

What is specific for this type of accelerators from beam instrumentation point of view

- Small fraction of lost beam matters
  - High dynamic range
- Damage threshold reached quickly
  - Fast response
- High power density
  - Non-intercepting diagnostics
- Strong space-charge effects

- Use of super-conducting RF linacs
  - New damage mechanisms
  - Clean environment

SNS has reached its design 1.4MW power!



Damaging Effects of Lost Beam

- Mechanical damage (melting, cracking, erosion)
- Activation of accelerator equipment

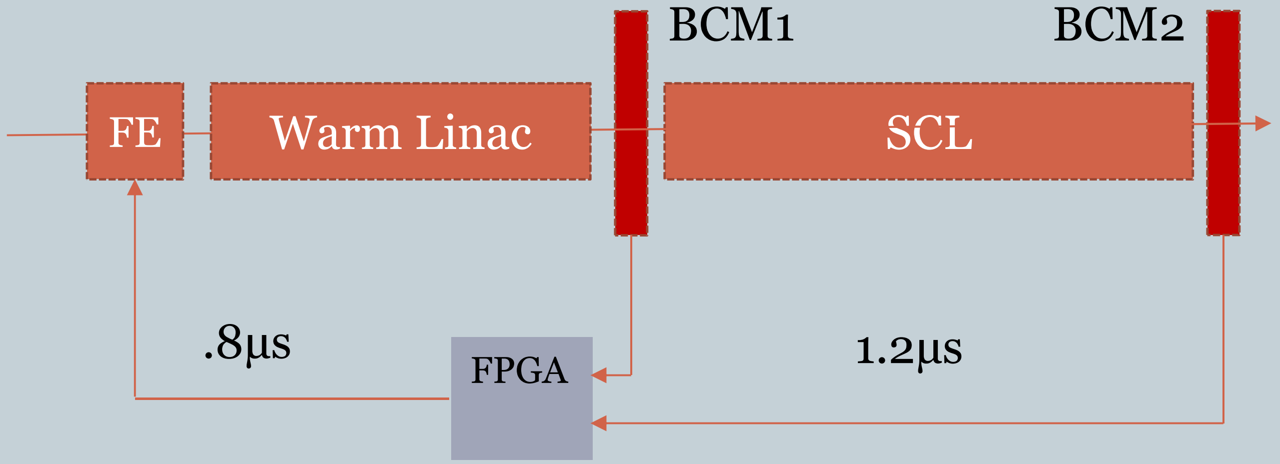
- SRF operation disruption
  - Load on cryogenic system
  - Effect on SRF cavity

Diagnostics for machine protection

- Radiation monitors at energy > 100Mev
  - 1 W/m requirement ~ $10^{-5} – 10^{-6}$ fractional loss
- Differential Beam Current Monitors < 10MeV
  - 100s W/m requirement ~ $10^{-1} – 10^{-2}$ fractional loss
- Combination of both in the transition area
- SRF specific problems:
  - 1W/m requirement is too low for RM and BCM in transition area
  - SRF cavity degradation due to repetitive instantaneous loss of ~ >250 J

How to protect Super Conducting Linac from errant beam loss

- Goal is to reduce shut off time for errant beam from ~25μs to 5-6μs
  - Time for abort signal propagation through MPS tree structure is 15-20μs
  - Dedicated protection system, bypassing MPS tree, to switch beam off quicker
  - MEBT chopper is used as fast switch off device



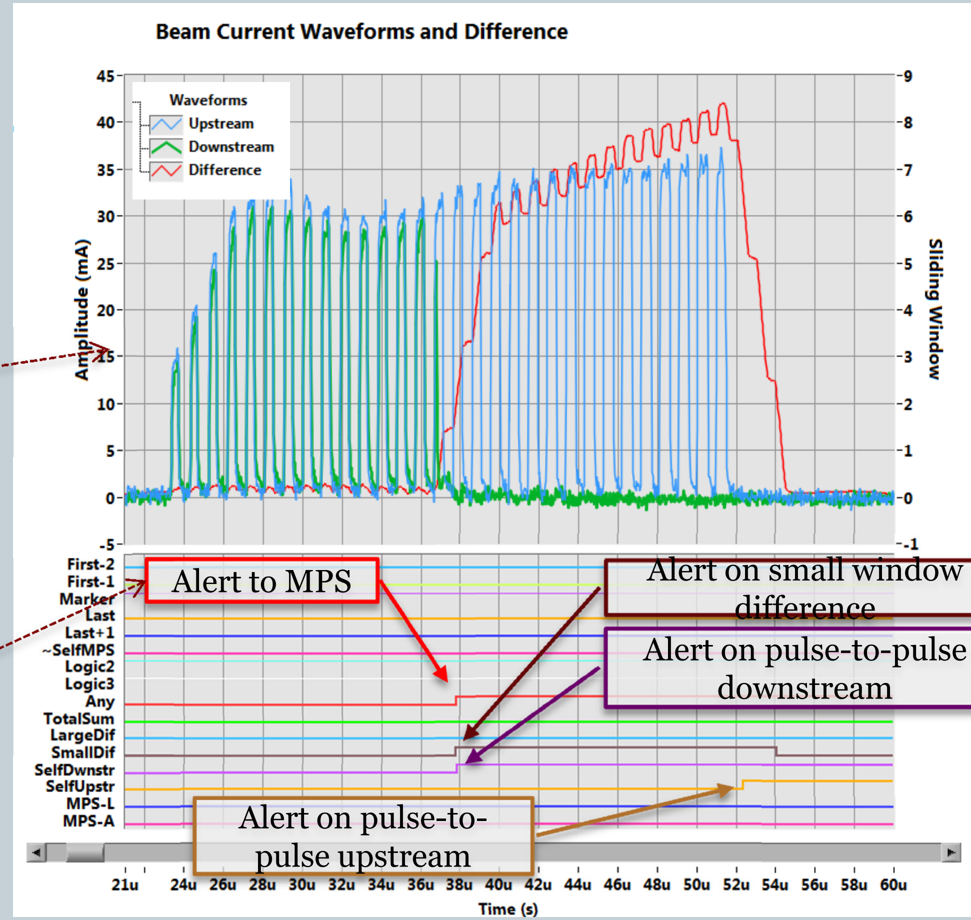
SNS Fast Differential Current Monitor

- Example of the errant beam we want to abort
- Analyzed to be due to a Warm Linac RF drop

Waveforms:

1. Upstream
2. Downstream
3. Difference after short sliding window

Alert was given in <1.5 μs (could be faster with lower thresholds and still avoid false alerts)



Charge and position measurements

- Typically non-intrusive (transformers, strip-lines)
- Signals are generally stronger with higher power
- Higher dynamic range and faster time response is required to satisfy operation at both full power and reduced power for tuning
  - SNS operational parameters: 26mA, 1ms, 60Hz
  - Anticipated tuning parameters: 26mA, 50us, 6Hz
  - SRF-safe tuning beam parameters: 5mA, 1us, 6Hz

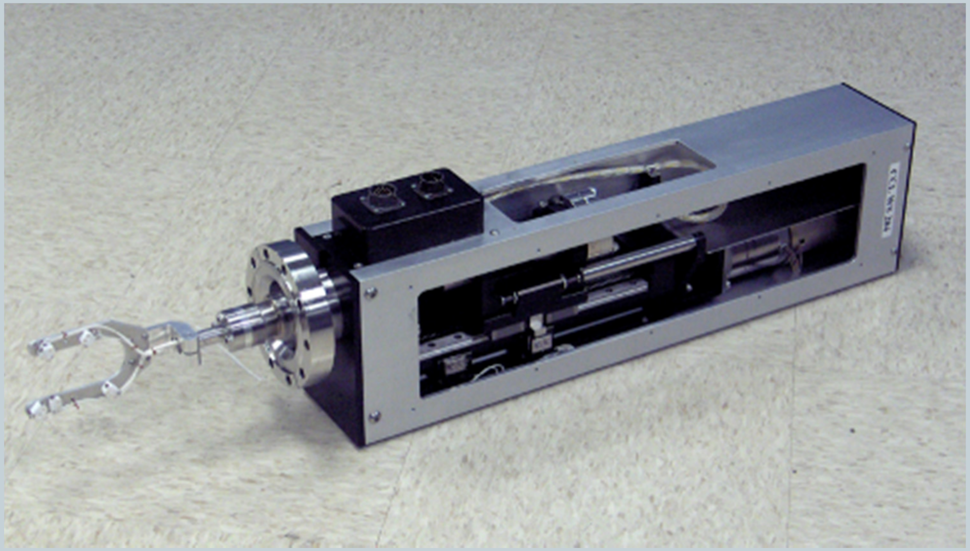
Charge distribution measurements (profile, emittance)

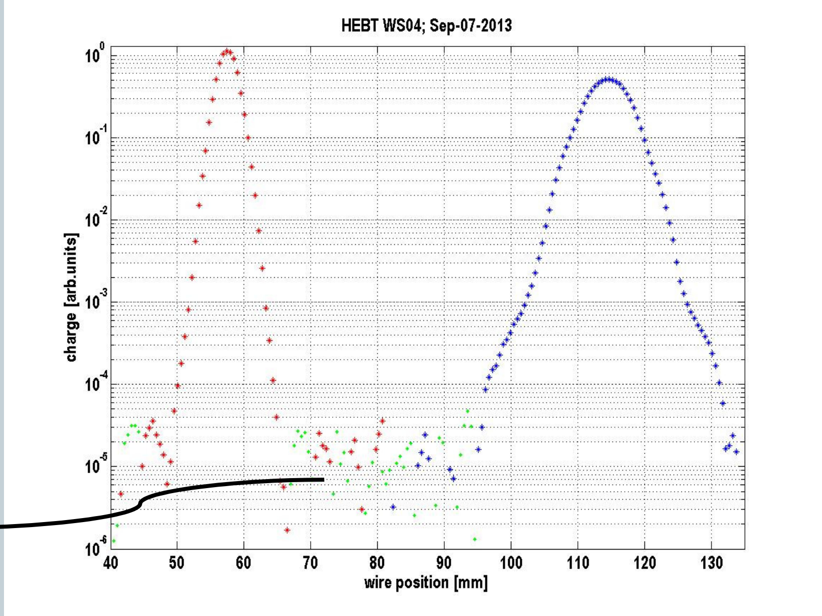
- Most challenging for high power beams
  - Need to have a “probe” inside beam
    - Probe survival under high power
  - Dynamics of small fractions of beam is of interest
    - Large dynamic range: 1MW/1W = 10^6
  - Time resolution for pulsed/chopped beams
- Hard to combine in one diagnostic
  - Separate measurements for different aspects of beam distribution

Probes for transverse profile measurements

	Dynamic range	Time resolution	Non-perturbing	In use at SNS
Solid material (wire, scraper, screen)	10^5 (10^6)	~10 ps	No	Yes
Photons (laser beam)	10^2 (10^4)	~10 ns	Yes	Yes
Charged particles (electrons, ions)	10	~10 ns	Yes	Yes
Gas (residual, jet)	10^2	~1 us	Yes	No

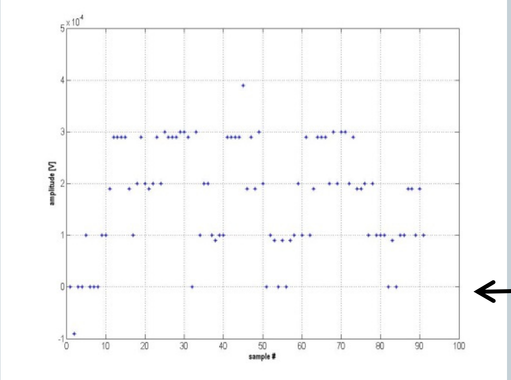
High dynamic range wire scanners at SNS





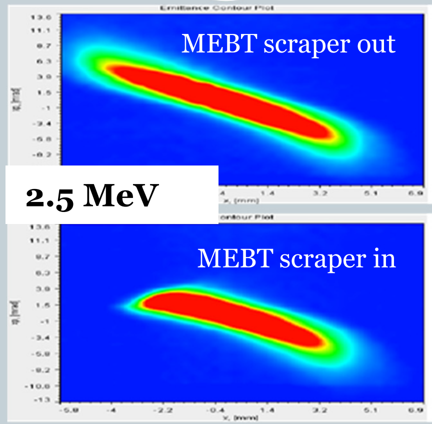
Dynamic range: 10^5

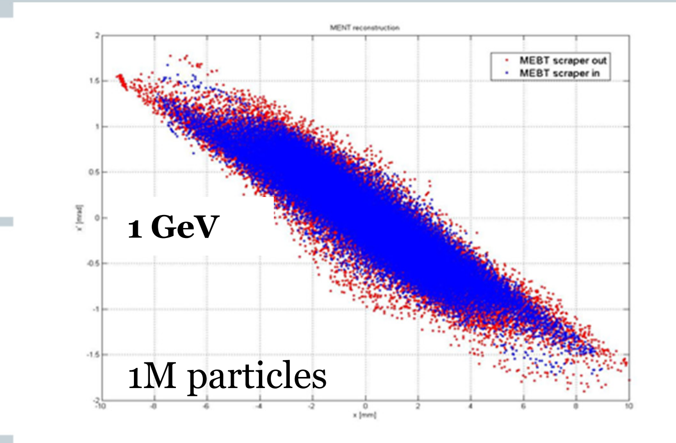
Time resolution: 1kHz

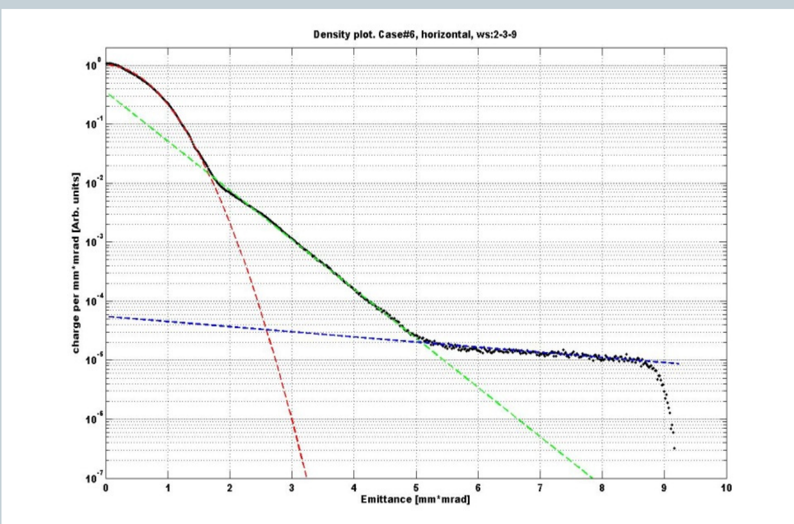


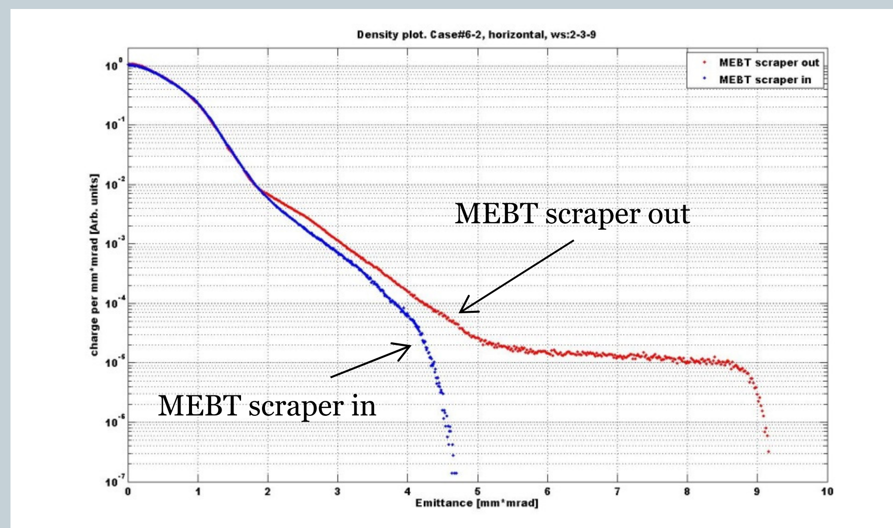
What do we do with high dynamic range profiles?

High resolution high quality profiles allow to reconstruct distribution in phase space

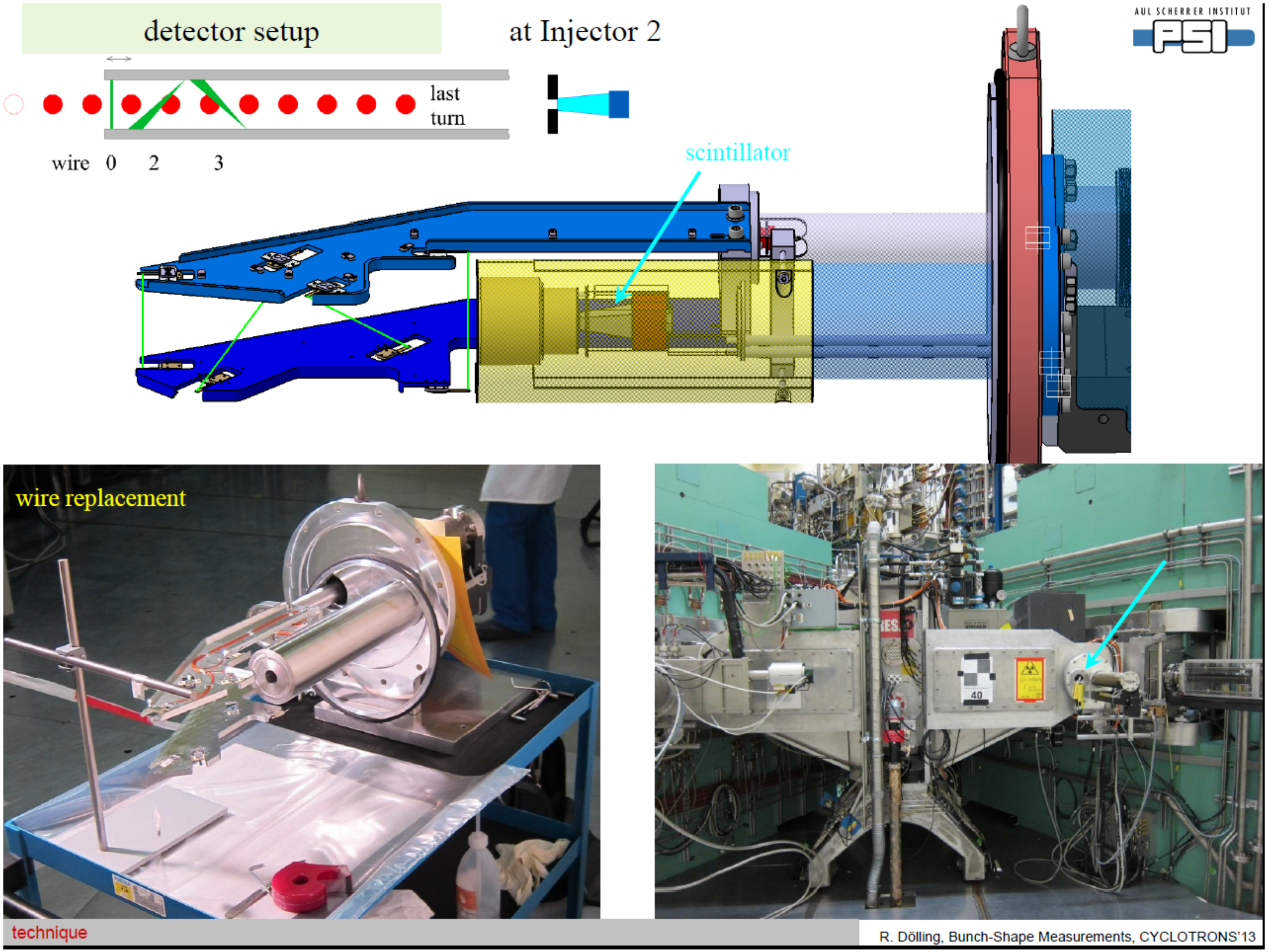




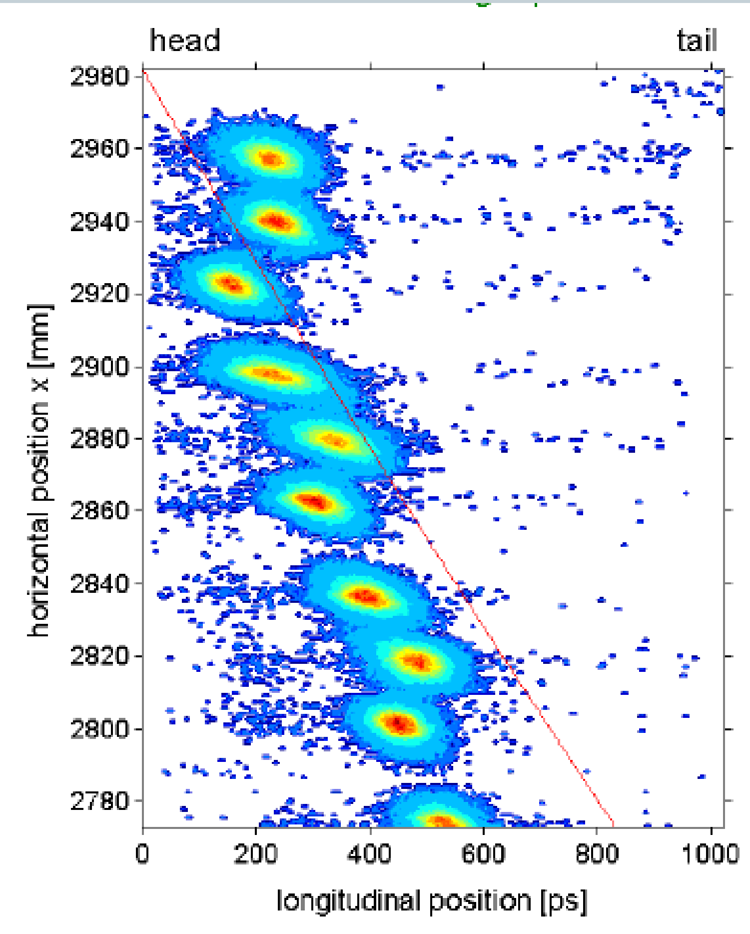




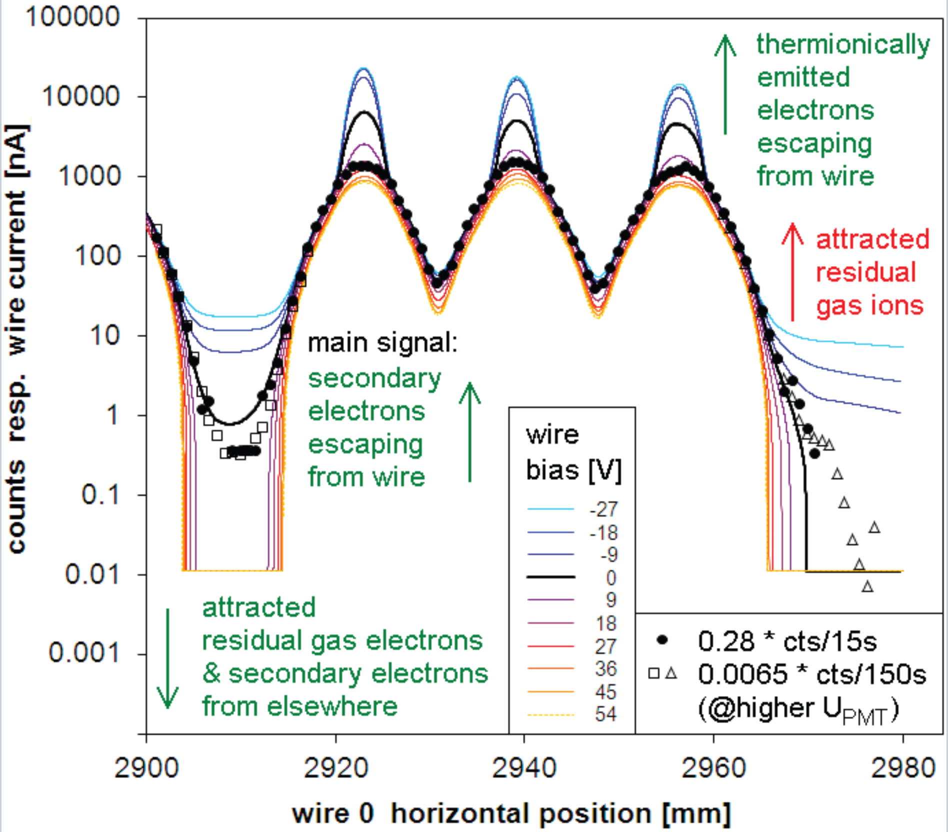
High resolution wire scanners at PSI



High time resolution and large dynamic range measurements on production beam at PSI



~15ps time resolution



~10^5 dynamic range

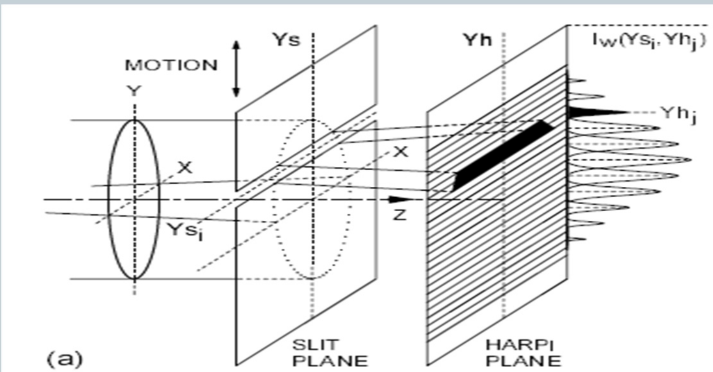
Courtesy of R. Dölling, PSI

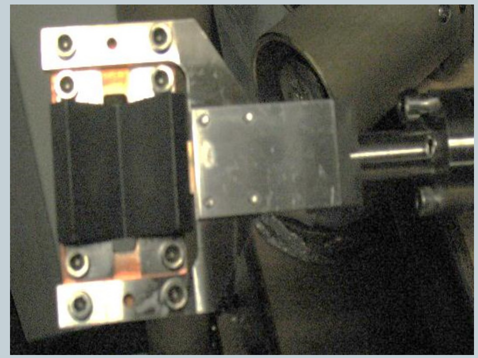
Conditions for achieving large dynamic range

- No significant beam loss nearby
- Good vacuum

- Injector is difficult place
  - Poor vacuum
  - Significant beam loss
  - Beam energy is too low for particle counting method

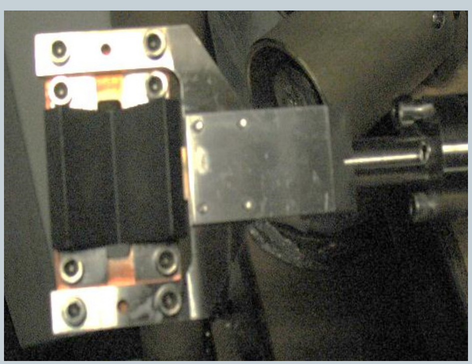
High resolution transverse distribution measurements at low energy with slits



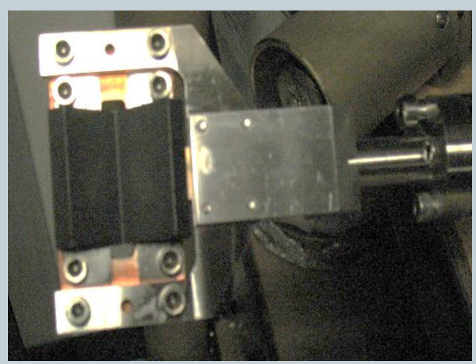


slit

harp

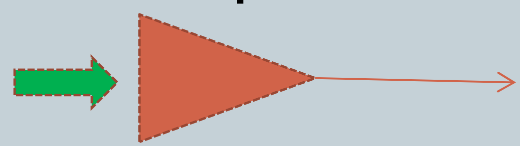


slit

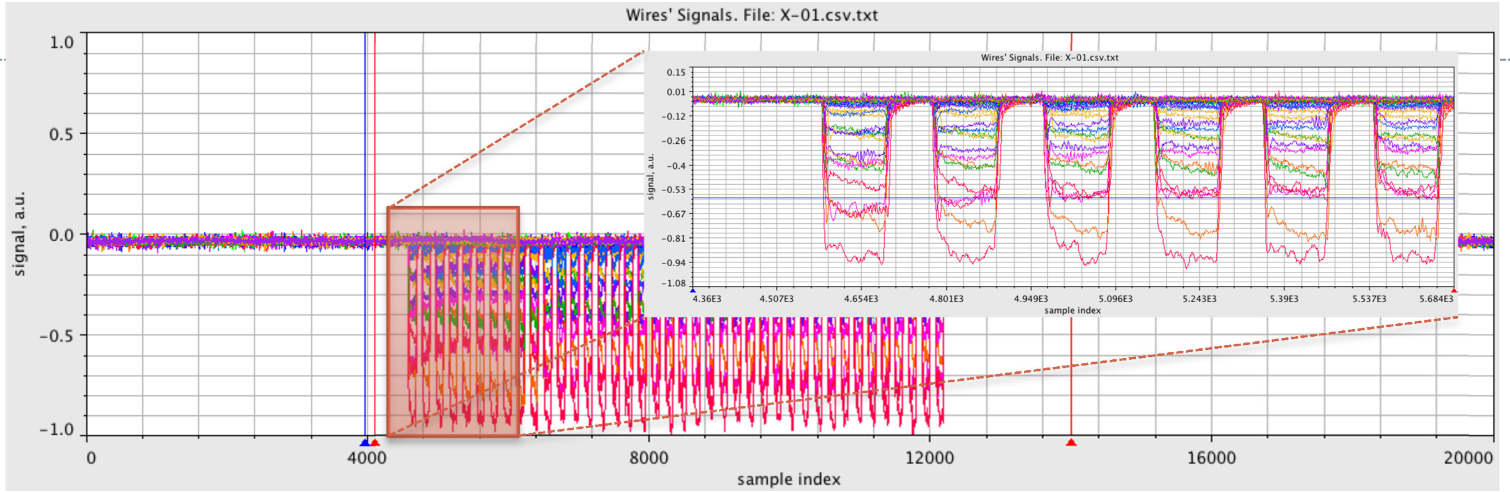


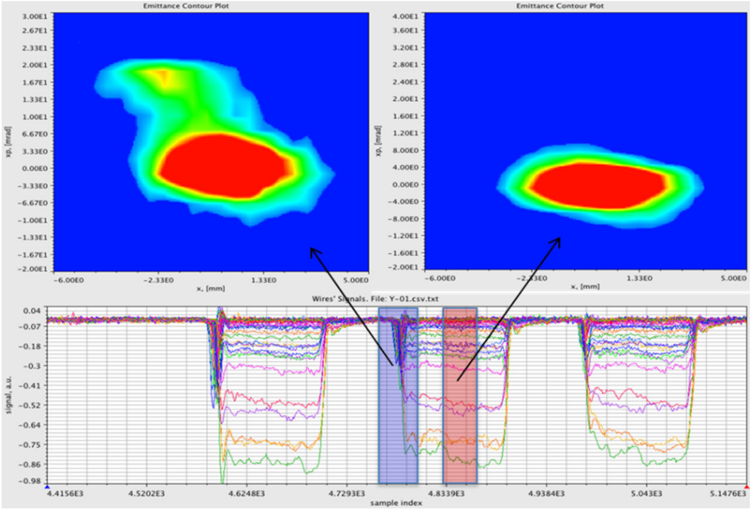
slit

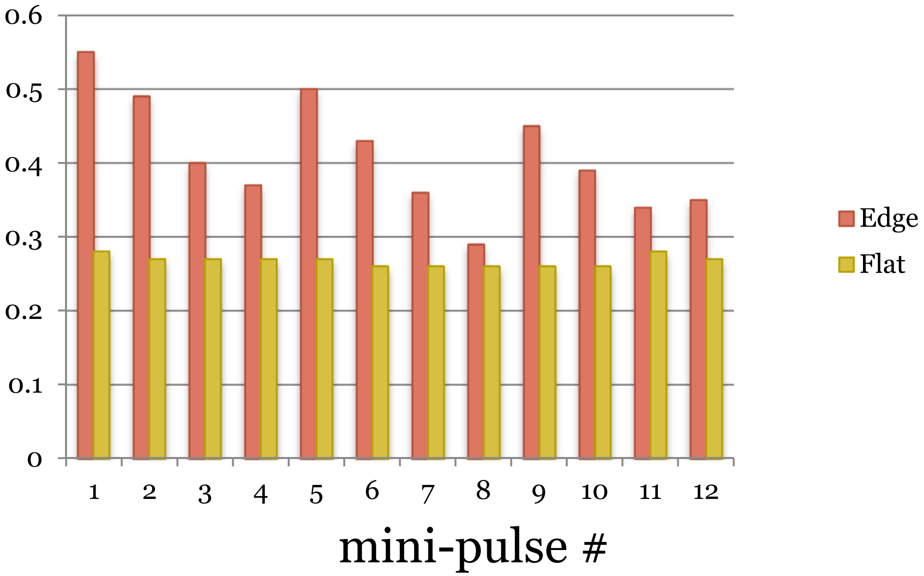
Faraday Cup



Higher time resolution

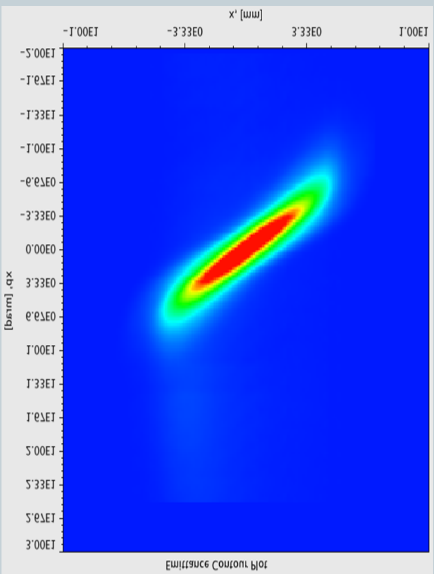




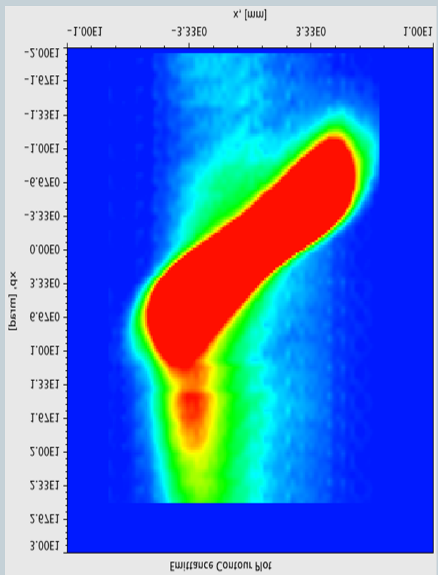


Higher dynamic range

slit - harp

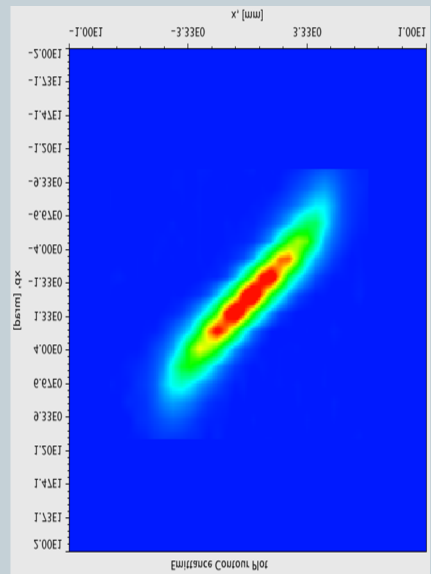


50% cut

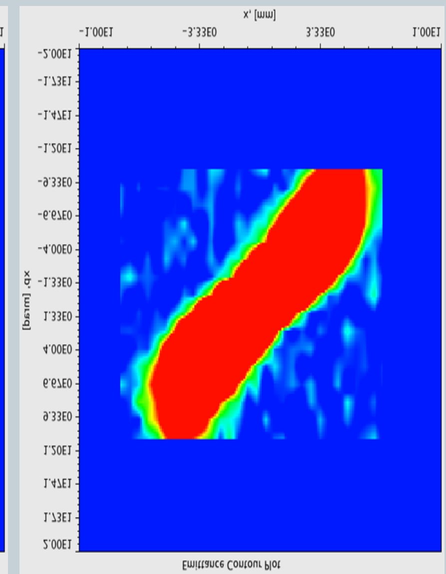


1% cut

slit - slit

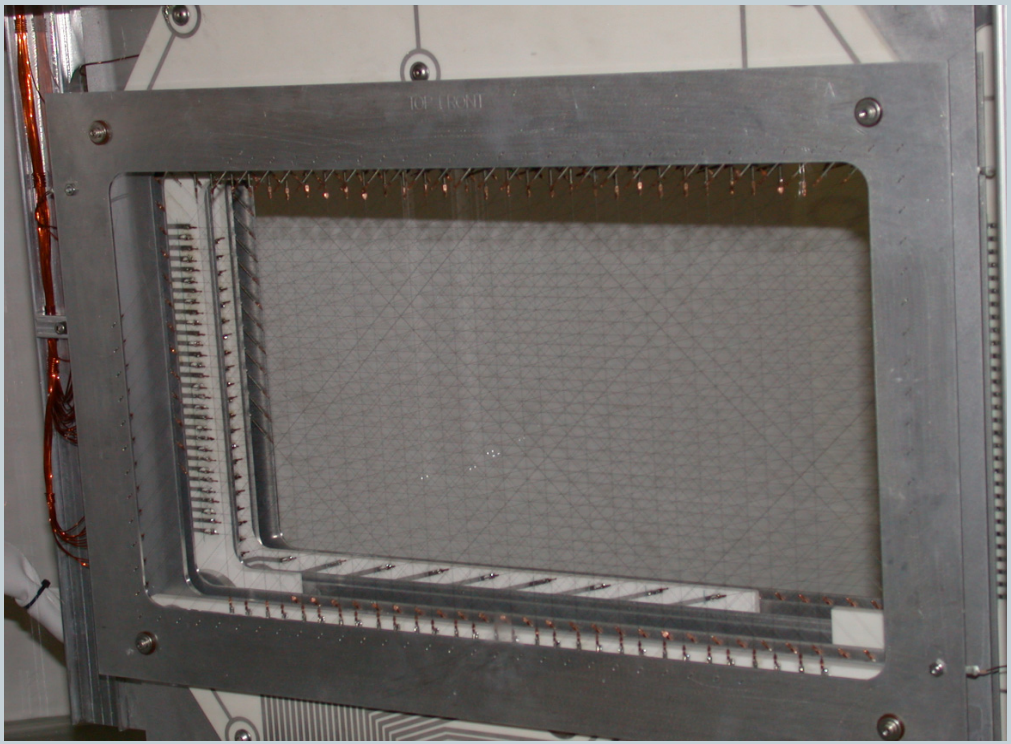


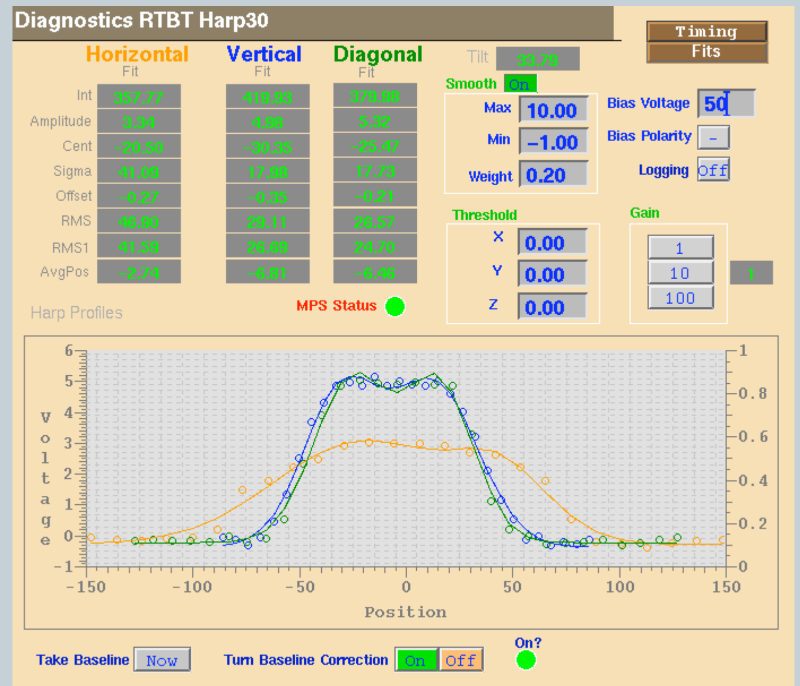
50% cut



1% cut

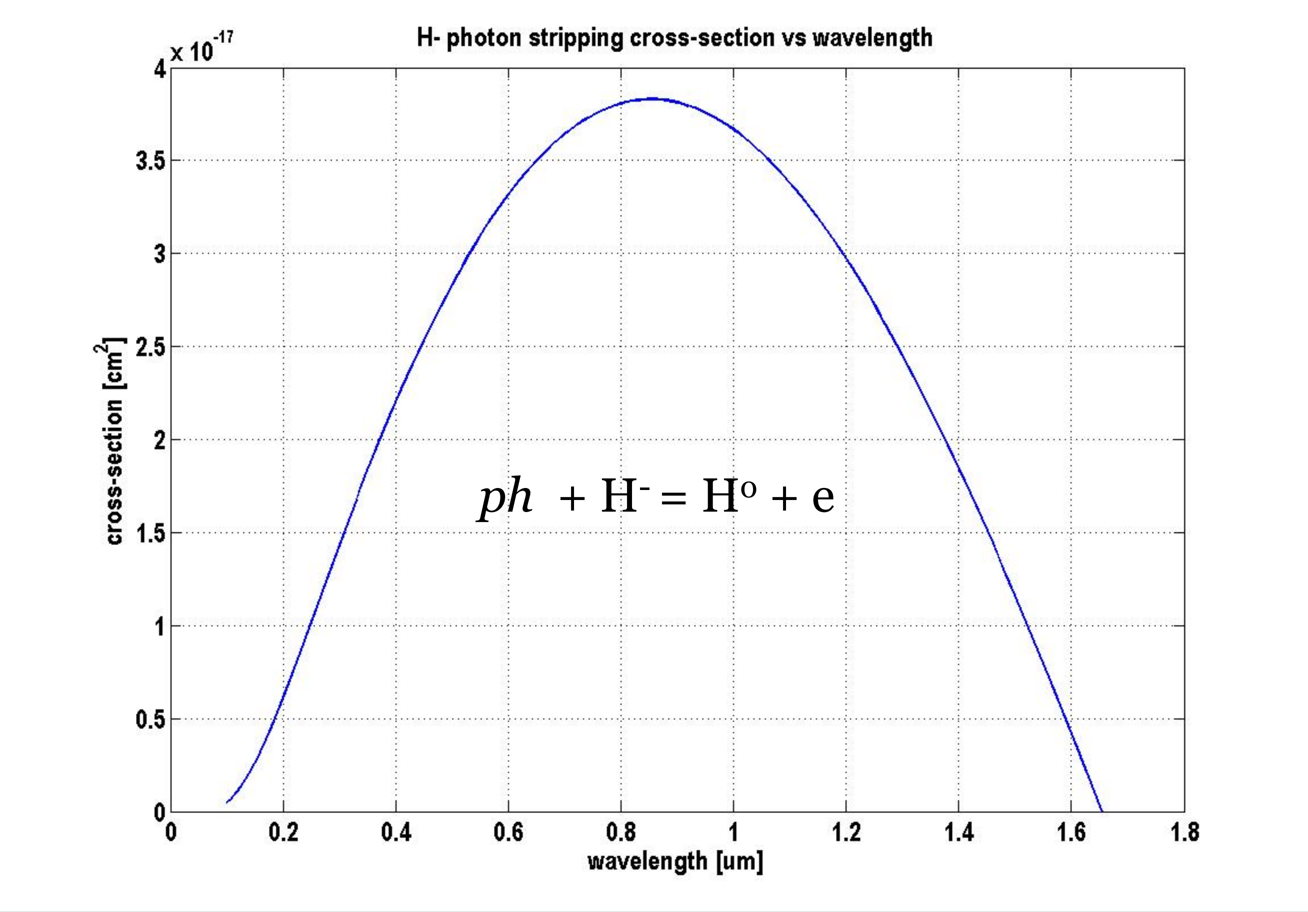
Charge distribution measurement with harp at SNS



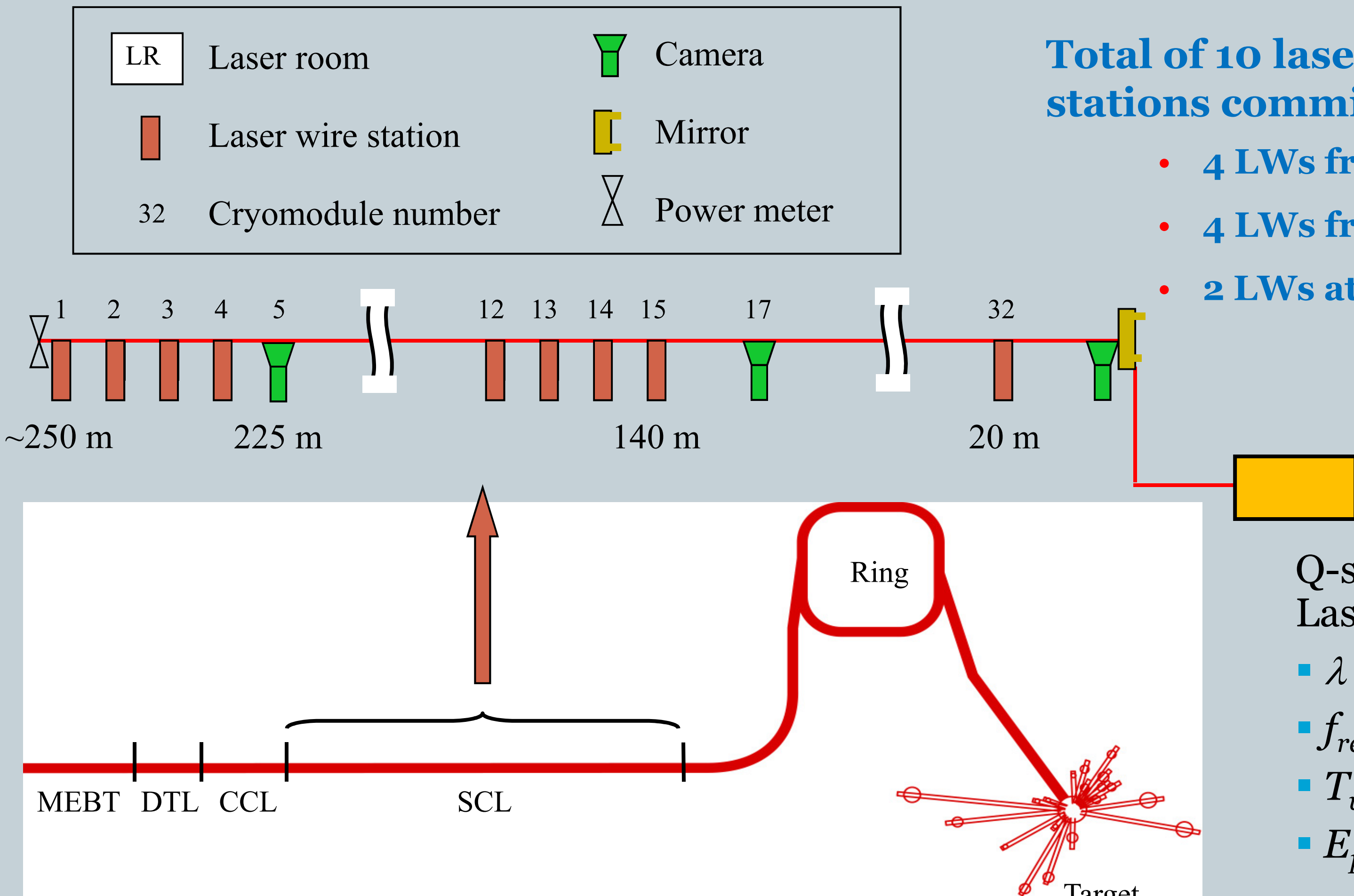


Harp is always inserted – "non-intercepting" diagnostic for 1GeV beam

Laser wire for H- profile measurement



Laser Wire System at SNS SRF Linac



Total of 10 laser wire stations commissioned:

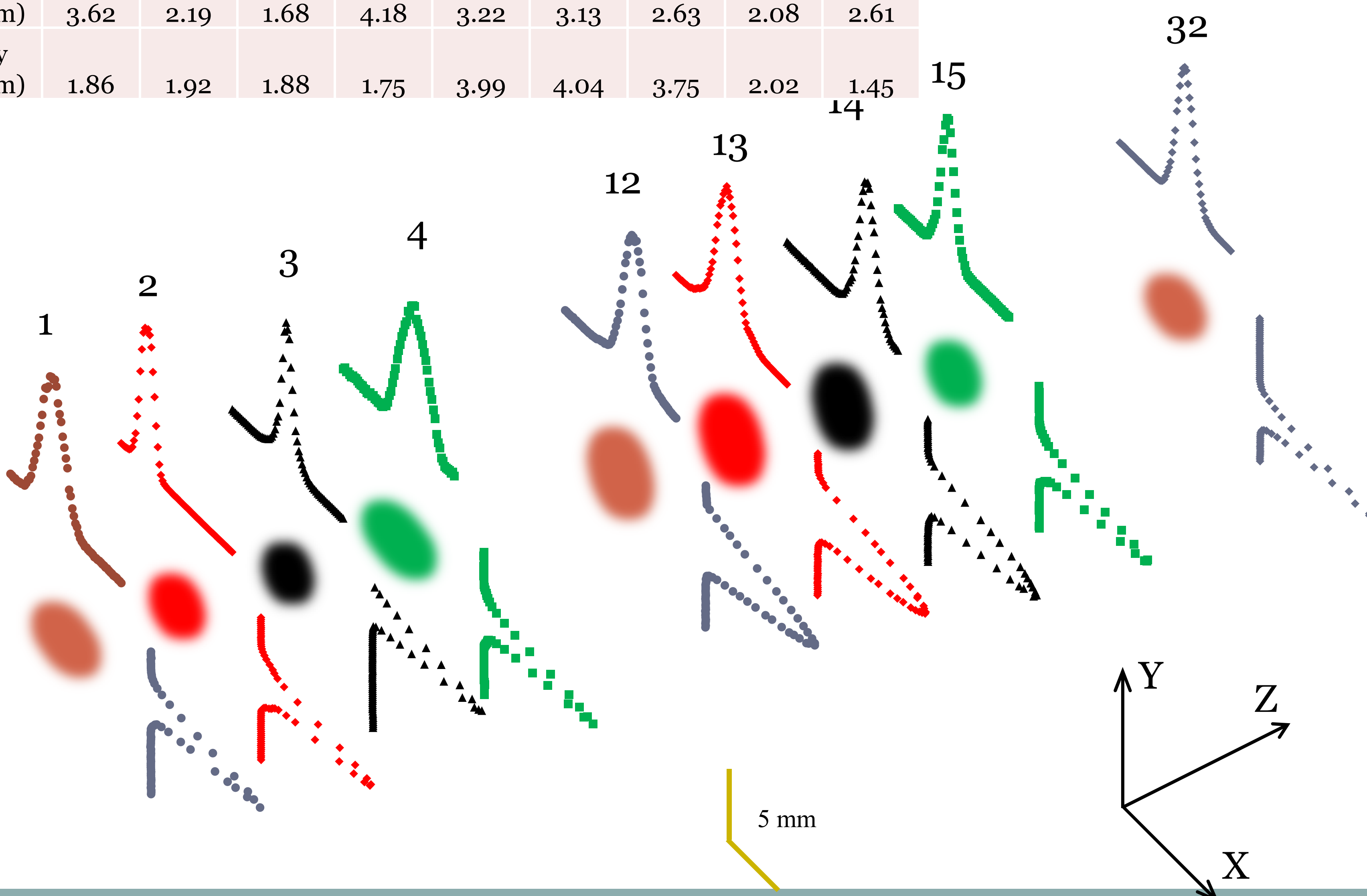
- **4 LWs from 200 MeV**
- **4 LWs from 450 MeV**
- **2 LWs at 1 GeV**

Q-switched Nd:YAG Laser

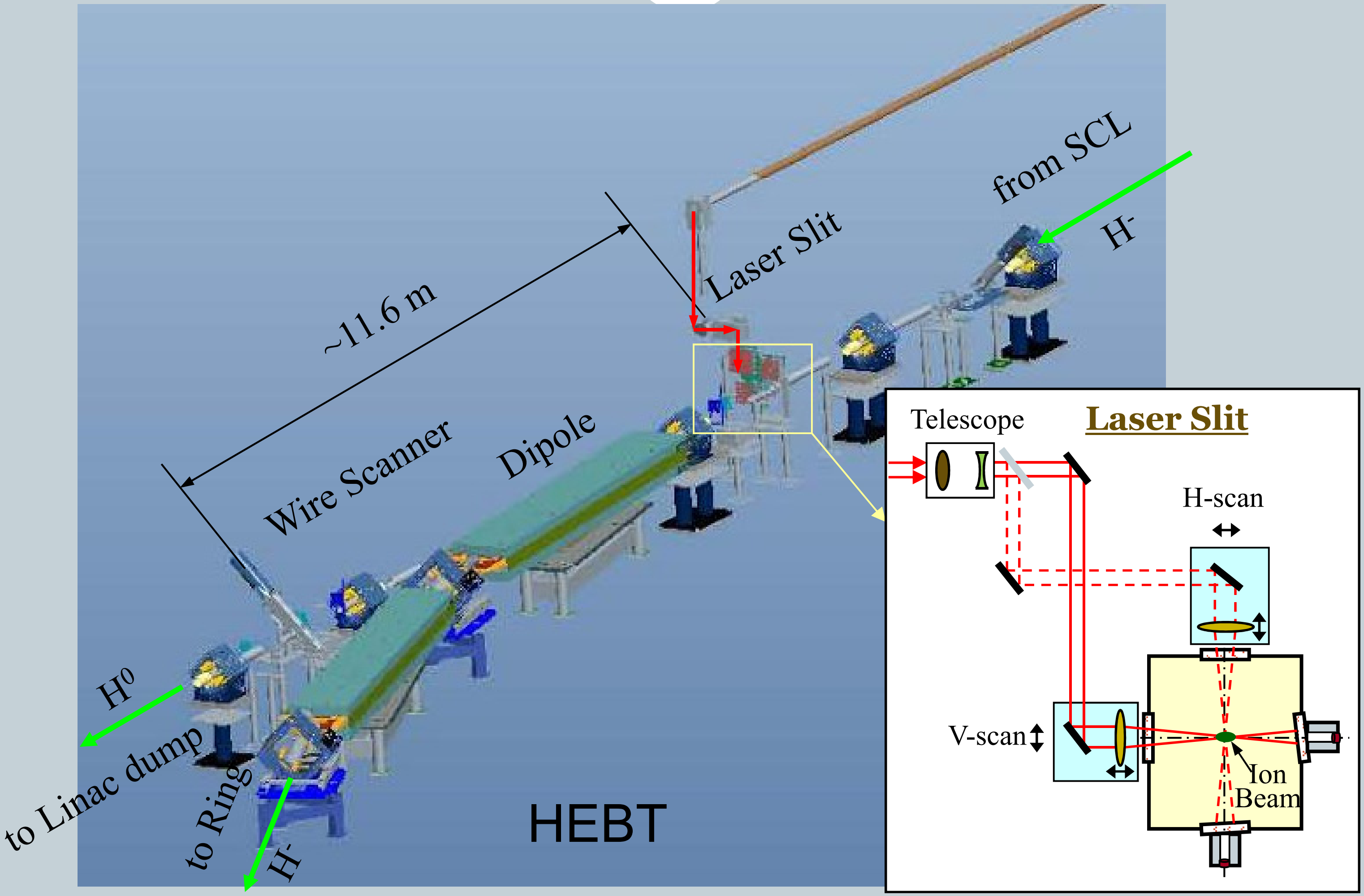
- λ = 1.06 µm
- f_{rep} = 30 Hz,
- T_w = 7 ns
- E_p = 1 J

SCL H- Profiles (1150 KW, Sept. 20, 2013)

	1	2	3	4	12	13	14	15	32
σx (mm)	3.62	2.19	1.68	4.18	3.22	3.13	2.63	2.08	2.61
σy (mm)	1.86	1.92	1.88	1.75	3.99	4.04	3.75	2.02	1.45



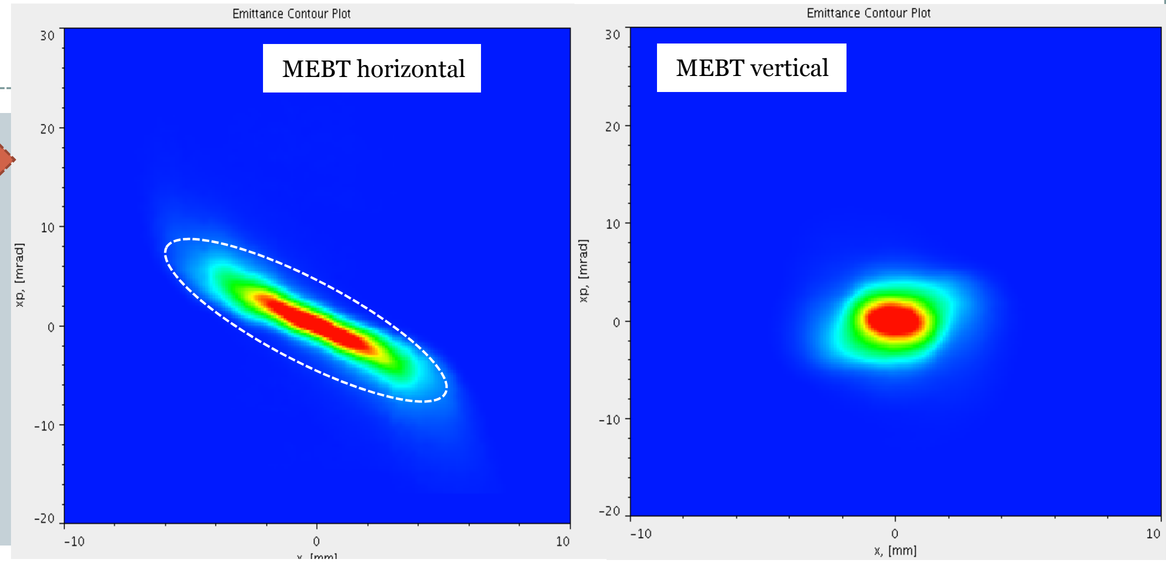
1GeV Laser Emittance Scanner at SNS



Emittance comparison at 2.5MeV and 1GeV

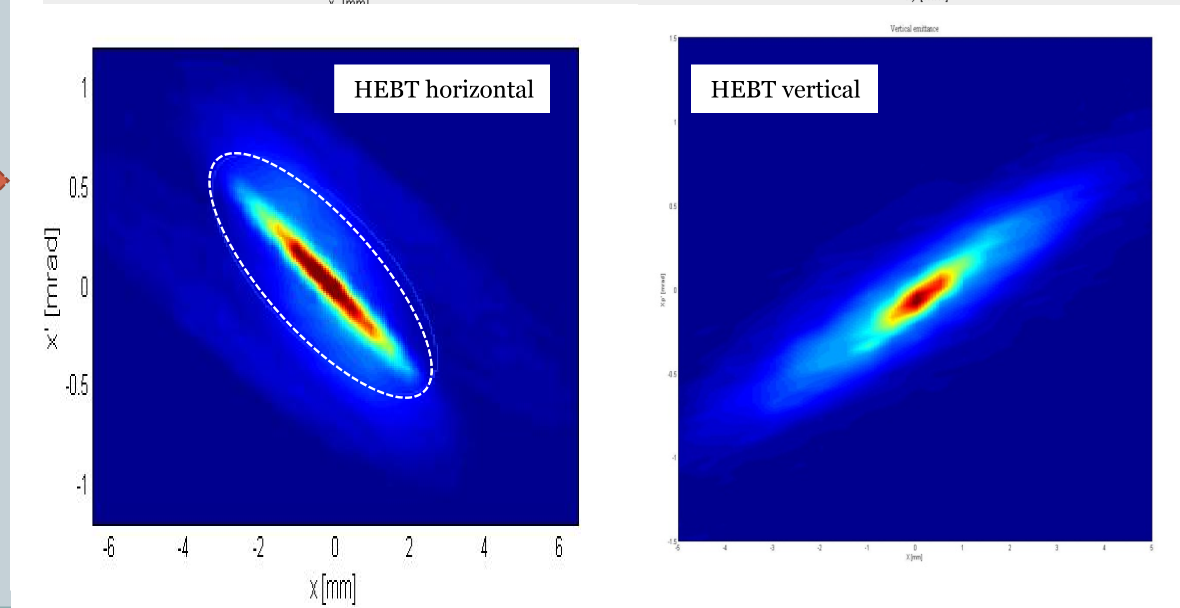
Emittance at 2.5 MeV

- dynamic range ~ 10,000
- Time resolution ~ 10 μs



Emittance at 1 GeV

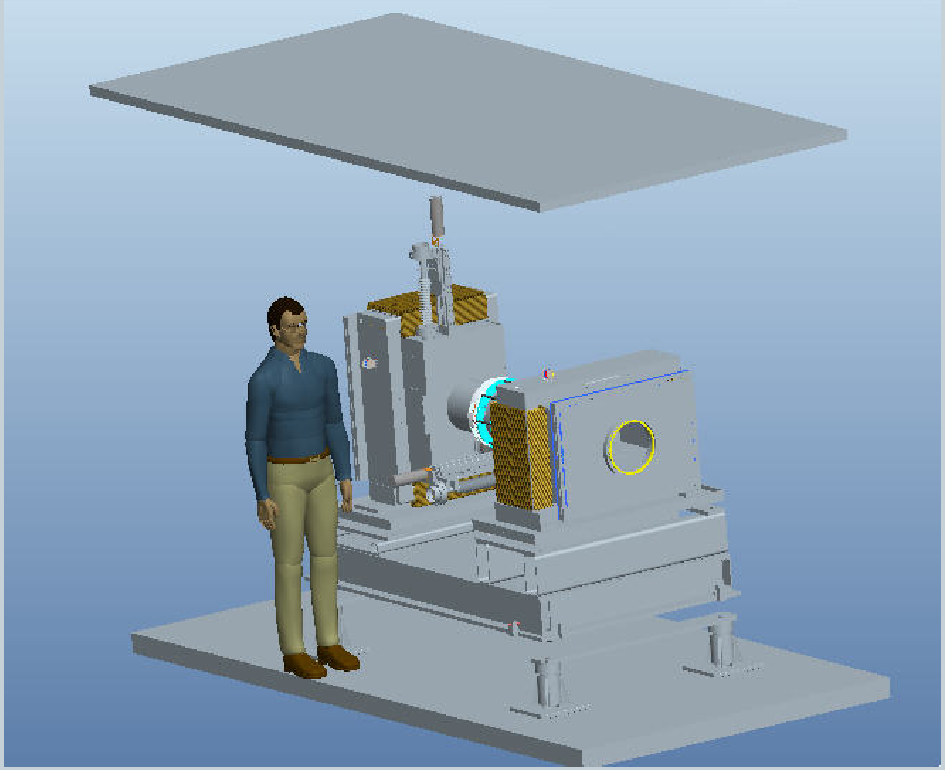
- dynamic range ~ 100
- Time resolution ~ 10 ns

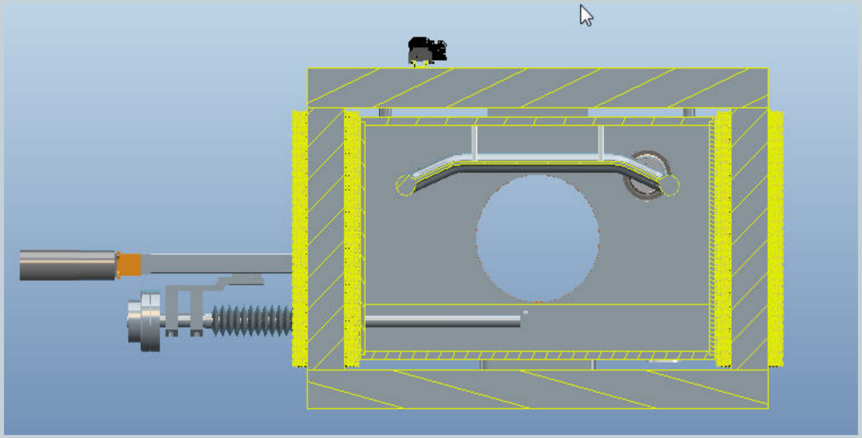


Laser Wire limitations

- Dynamic range
  - Limited by reflections from vacuum windows
  - Signal-to-noise = 10^4
- Only works with H^- beam

Ionization Profile Monitor design for SNS Accumulator Ring

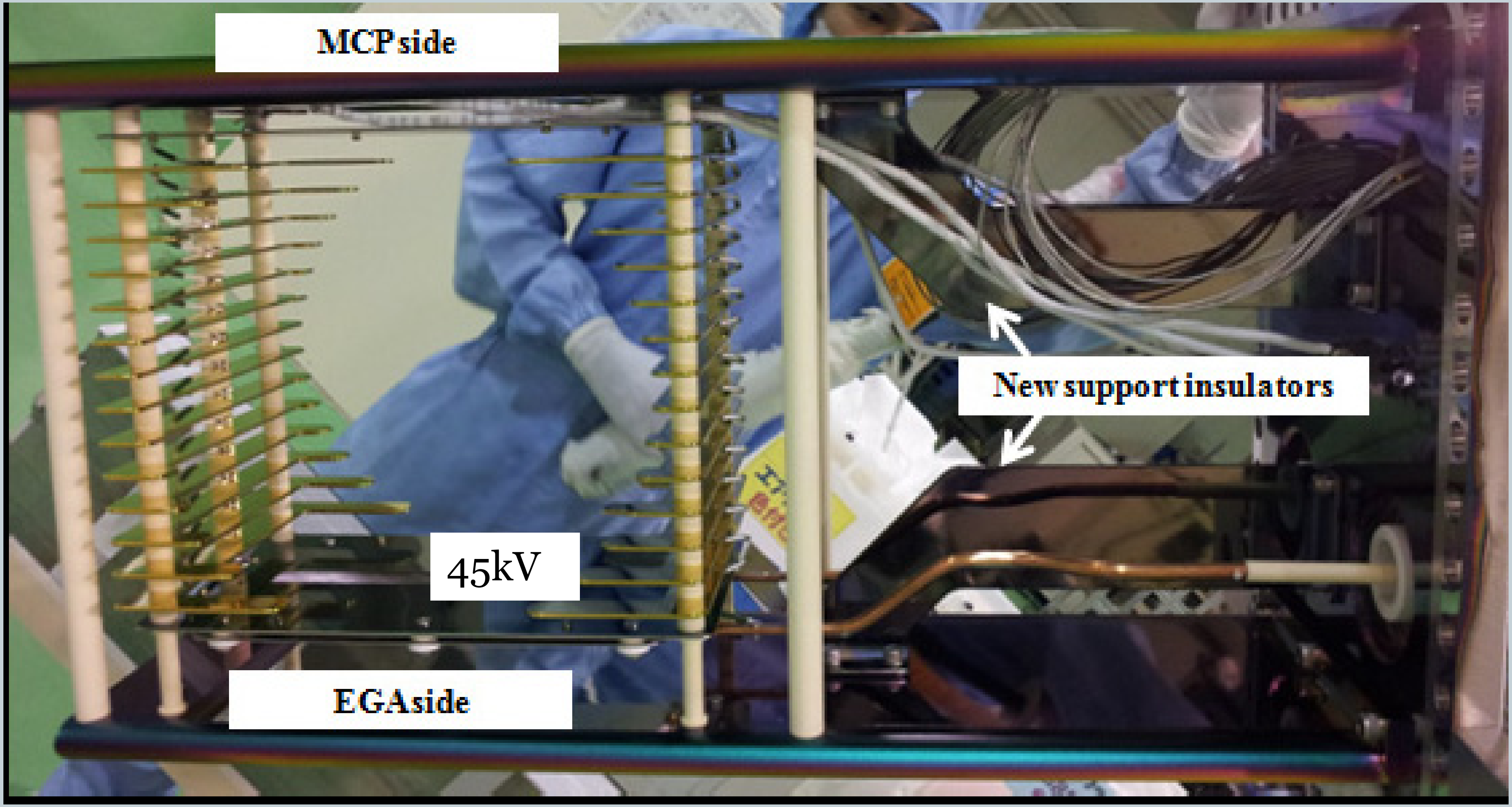




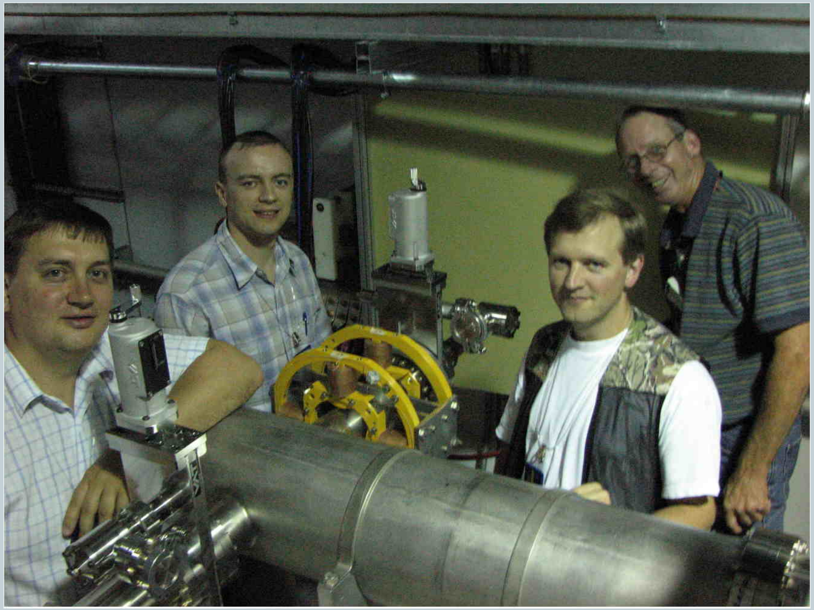
Design parameters

bias voltage	120kV
dynamic range:	100
time resolution:	20 ns
spatial resolution:	1 mm

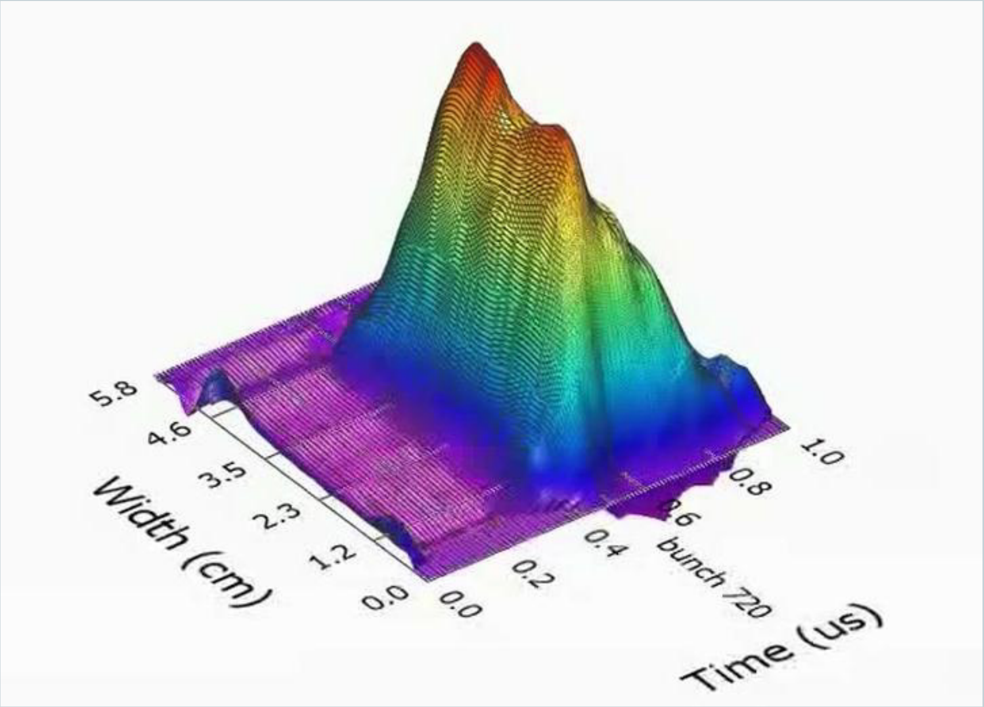
Ionization Profile Monitor at J-PARC



Electron beam probe at SNS ring

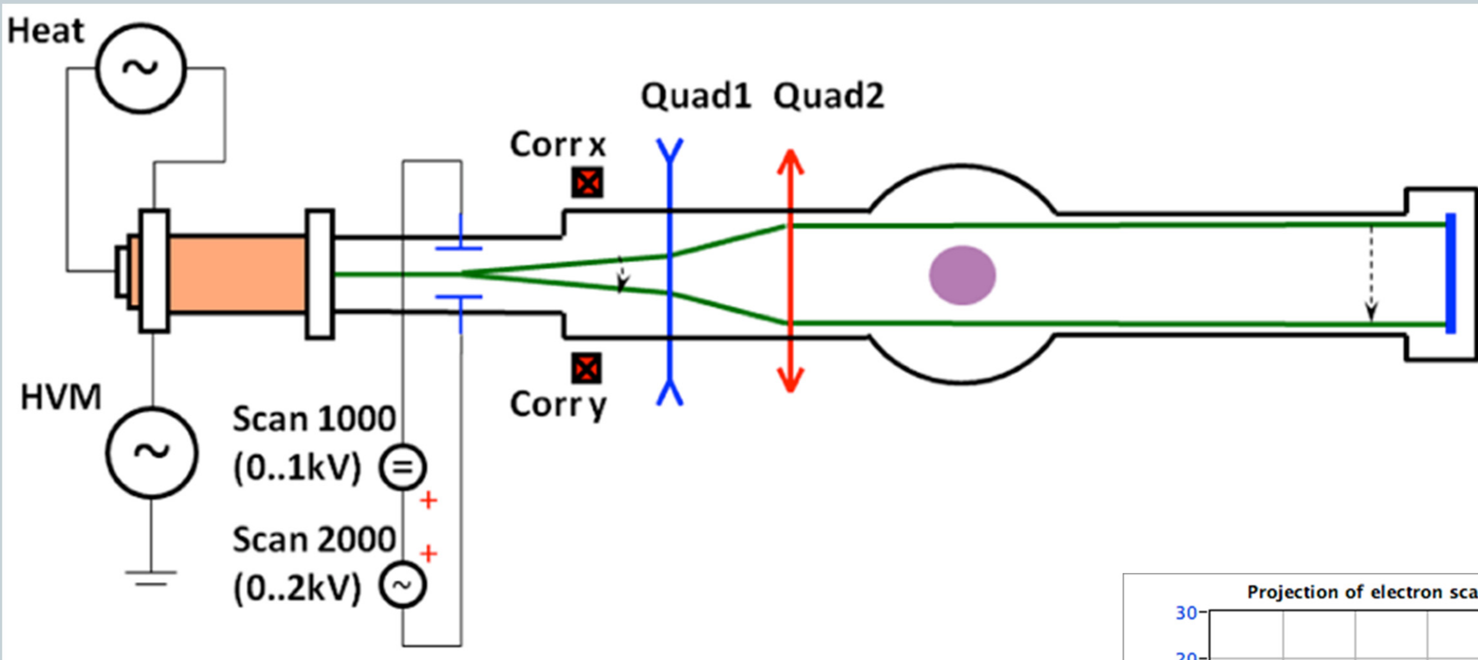


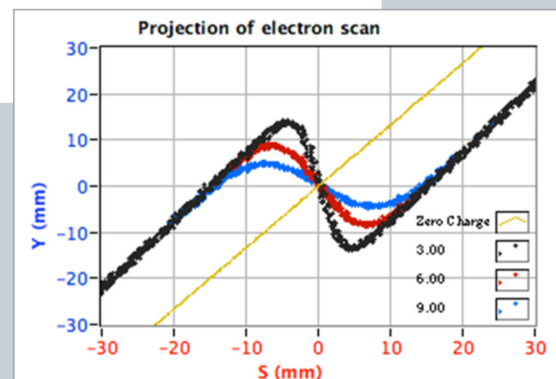
Electron beam scanner in SNS Ring



Time-resolved transverse beam profile in SNS Ring

Electron beam probe principle of operation





- Dynamic range: 10
  - fundamental limit of the method
- Time resolution: >10 ns
  - Deflector speed

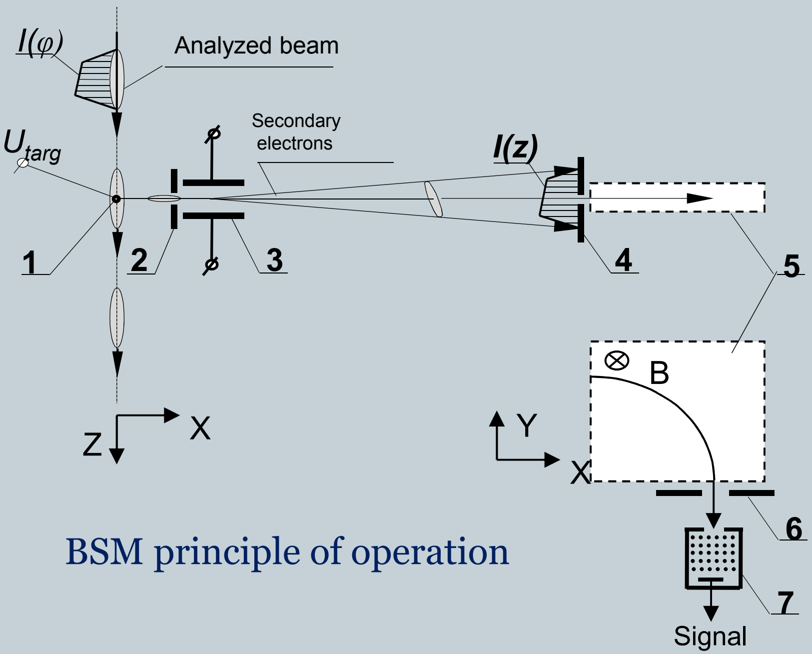
Luminescence monitor

- Count rate is typically even lower than for IPM
  - Storage rings
  - CW linacs
- Can have advantage for
  - Multi-charged ions
  - Low energy
  - Poor vacuum
  - Very high current
- No promise of large dynamic range or time resolution

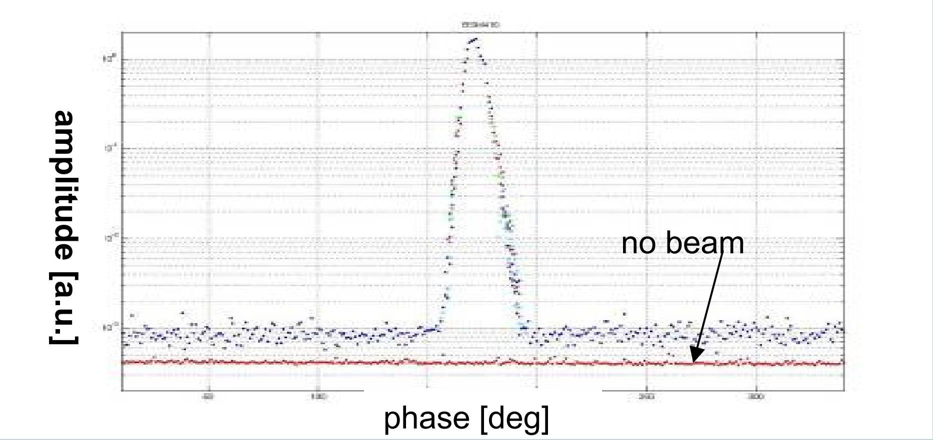
Probes for longitudinal profile measurements

	Dynamic range	Time resolution	Non-perturbing	In use at SNS
Solid material (wire)	10^4	1 ps	No	Yes
Photons (laser beam)	10^2	10 ps	Yes	Yes
Charged particles (electrons)	?	?	Yes	No
Residual Gas	?	?	Yes	No

Beam Shape Monitor (aka Feschenko Monitor)

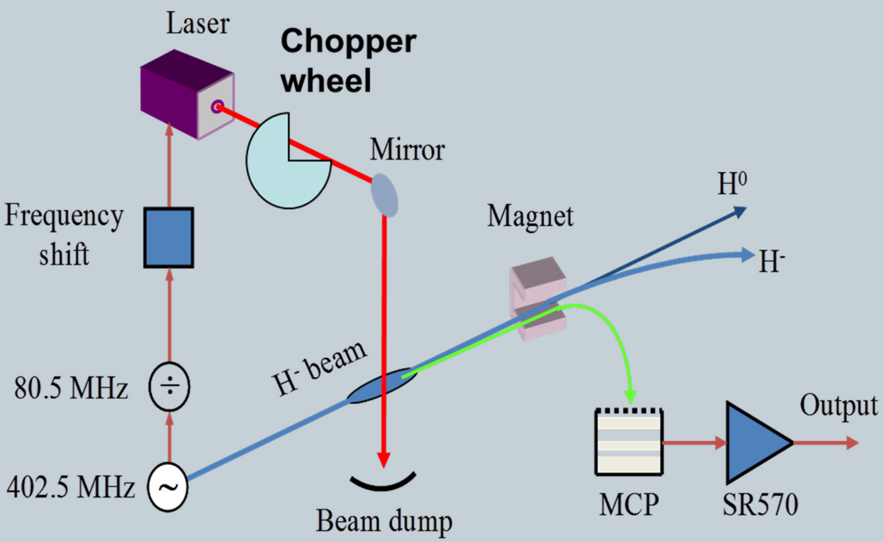


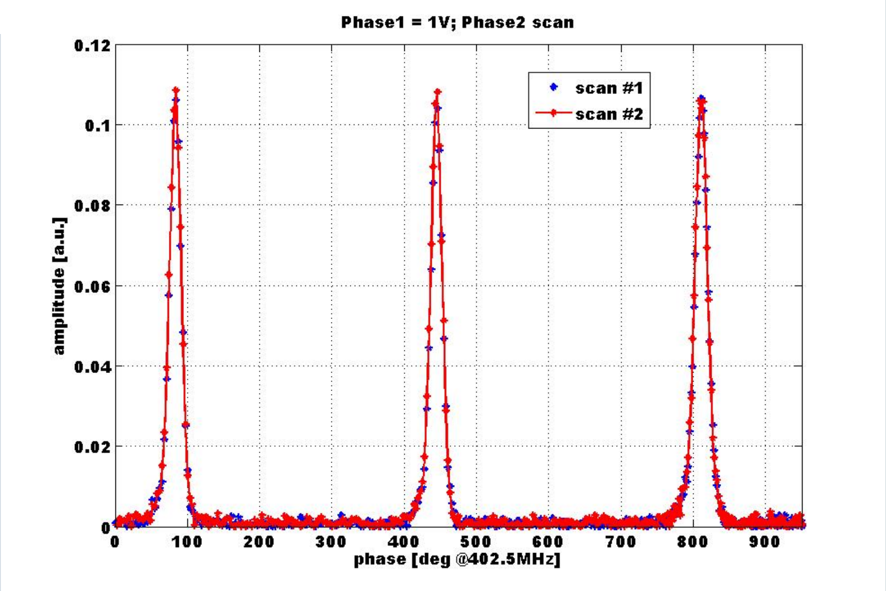
BSM principle of operation



- Dynamic range: 10^4
  - limited by radiation background
- Time resolution: >1 ps
  - limited by space charge

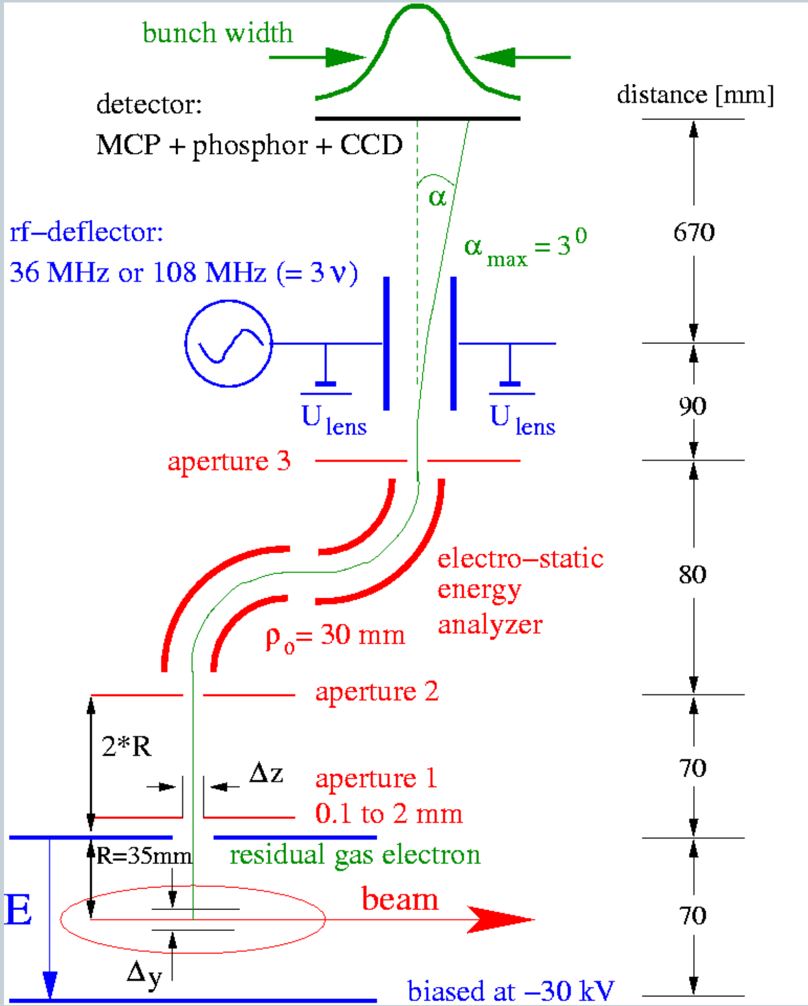
Laser Bunch Shape Monitor at SNS injector (2.5MeV)





- Dynamic range: 10^2
  - limited by residual gas stripping
- Time resolution: >10 ps
  - limited by beam transverse size

Novel Type of non-intercepting Bunch Shape Measurement



Scheme for non-intercepting device:

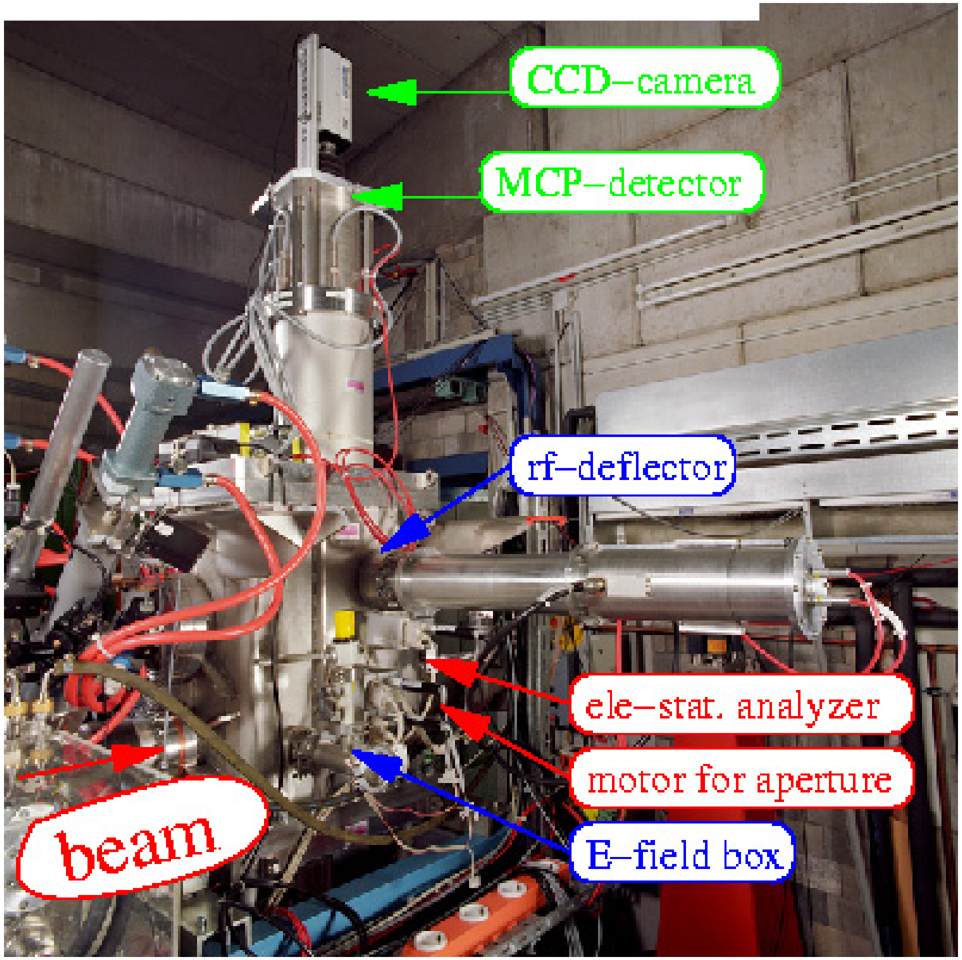
- Secondary electrons from residual gas
- Acceleration by electric field
  (like for Ionization Profile Monitor)
- Target localization by apertures
  and electro-static analyzer
  (Δy = 0.2 to 2 mm, Δz=0.2 to 1 mm)
- rf-resonator as 'time-to-space' converter
  $\lambda/4$ resonator, $Q_0 \approx 300$, P_{in}=50 W max.
- Readout by MCP + Phosphor + CCD
- Measurement done within one macro-pulse
  (presently: few pulses due to background)

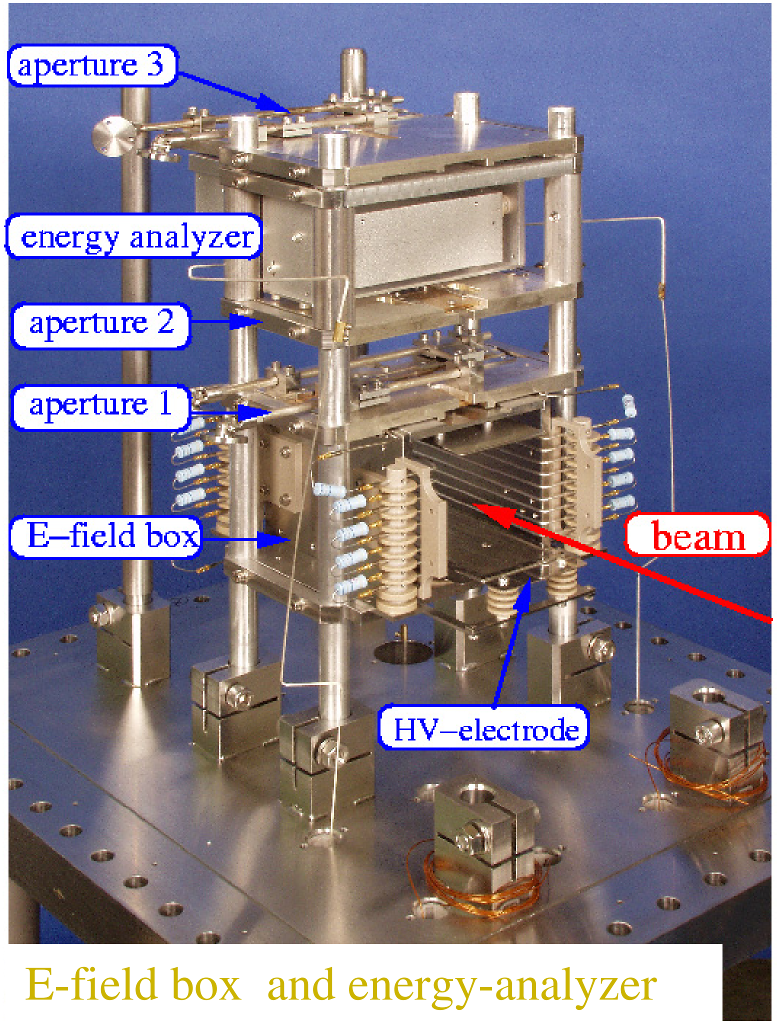
⇒ **Conclusion**: Quite complex device !

Courtesy of P. Forck, GSI

Realization for non-intercepting Bunch Shape Monitor

The installation for beam based tests

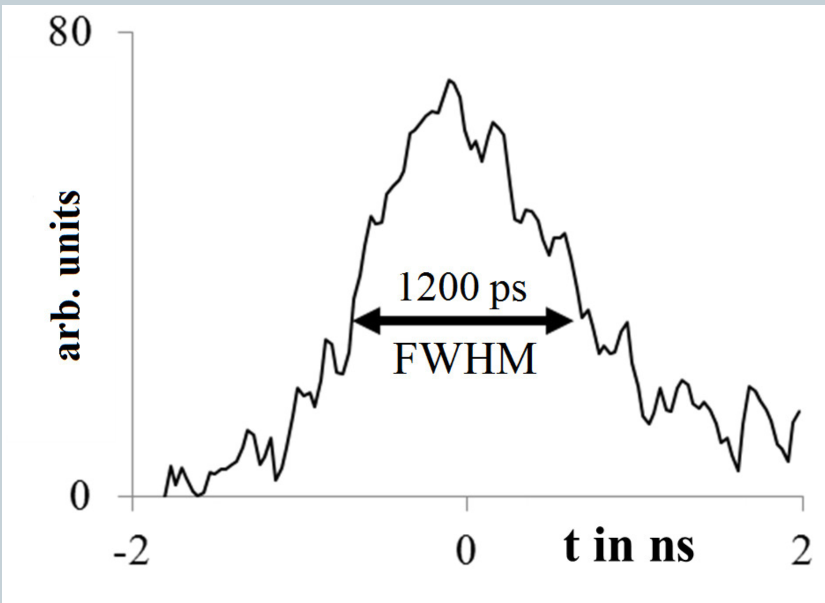


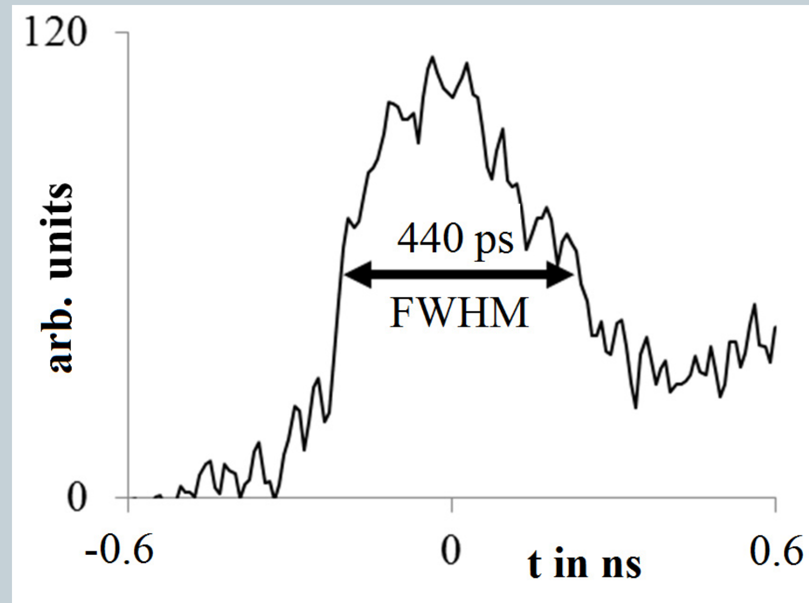


E-field box and energy-analyzer

Courtesy of P. Forck, GSI

non-intercepting BSM results





Parameters: U36+, I = 100 µA, =
180 µs, p = 5 · 10−6 mbar,

Courtesy of P. Forck, GSI

Summary

- Use of SRF technology for high power beams introduces new challenges for machine protection
- Diagnostics for charge distribution measurements with high dynamic range are most challenging
  - Interceptive methods can provide very large dynamic range and high time resolution
  - Laser based diagnostics can be ultimate solution for H- beams: non-interceptive, high dynamic range and time resolution
  - There is no operationally proved (yet!) non-interceptive diagnostics for other beams with large dynamic range and high time resolution