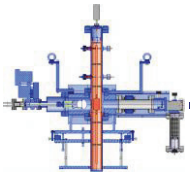
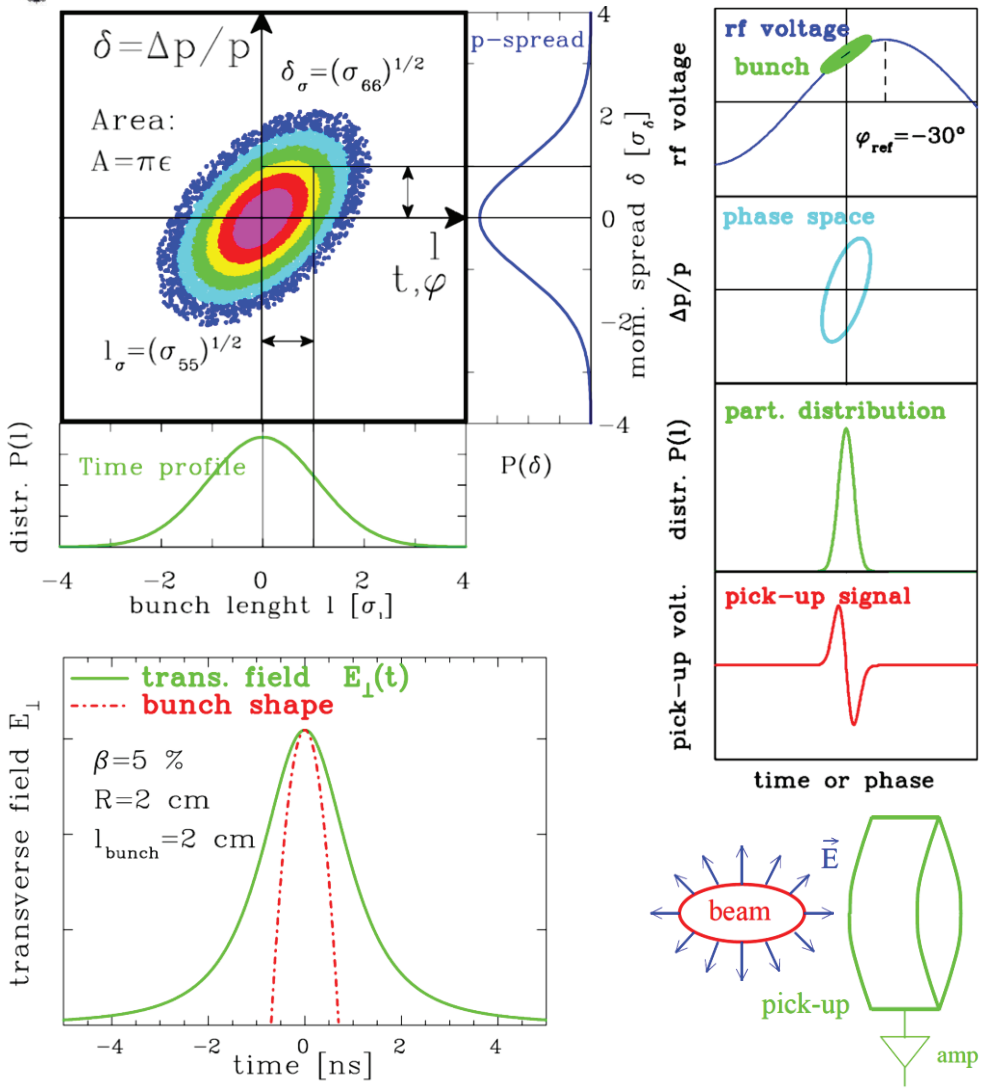


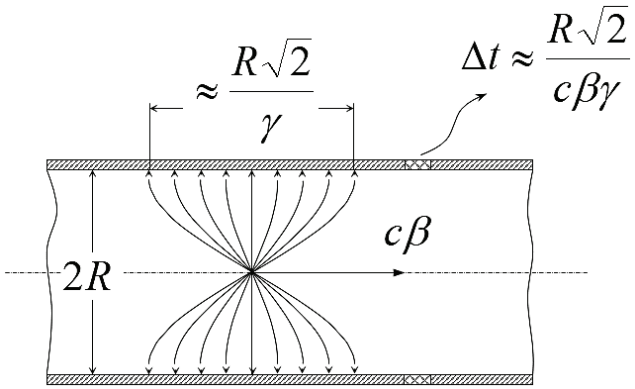
Development & implementation of bunch shape instrumentation for ion linacs

Alexander V. Feschenko,
Victor A. Gaidash,
Sergei A. Gavrilov
Institute for Nuclear Research RAS

Concept briefing

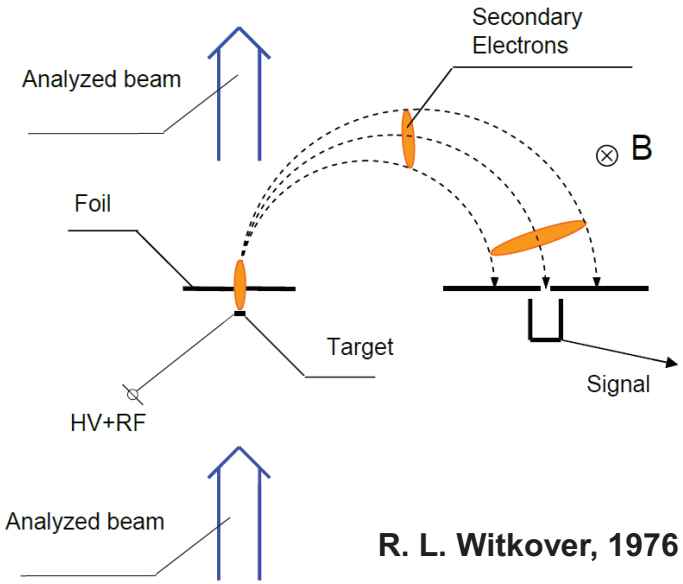


Courtesy of P. Forck (GSI)



protons 100 MeV, R = 20 mm
equivalent bandwidth ~ 2.5 GHz

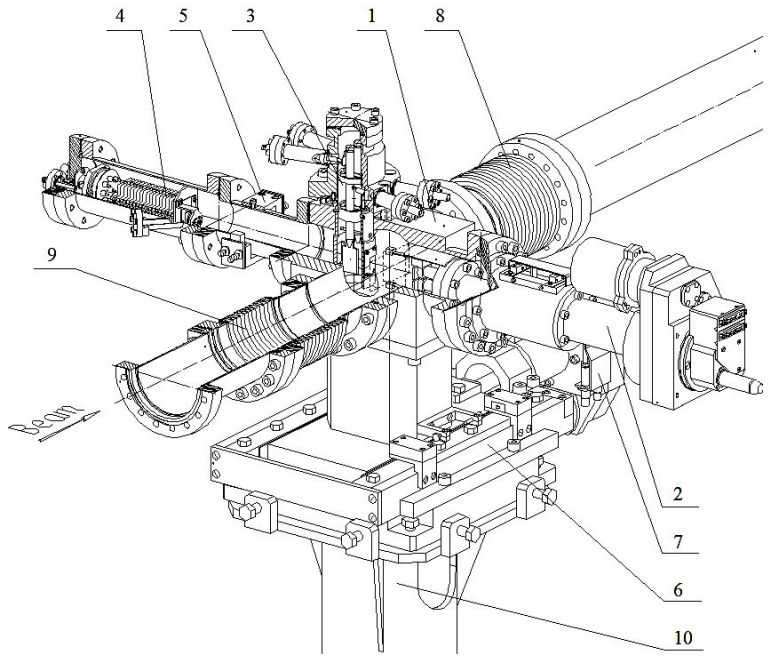
The only practical method for ion linacs:
secondary electrons



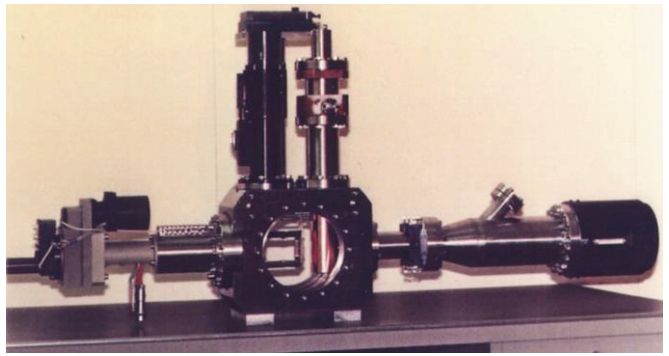
R. L. Witkover, 1976

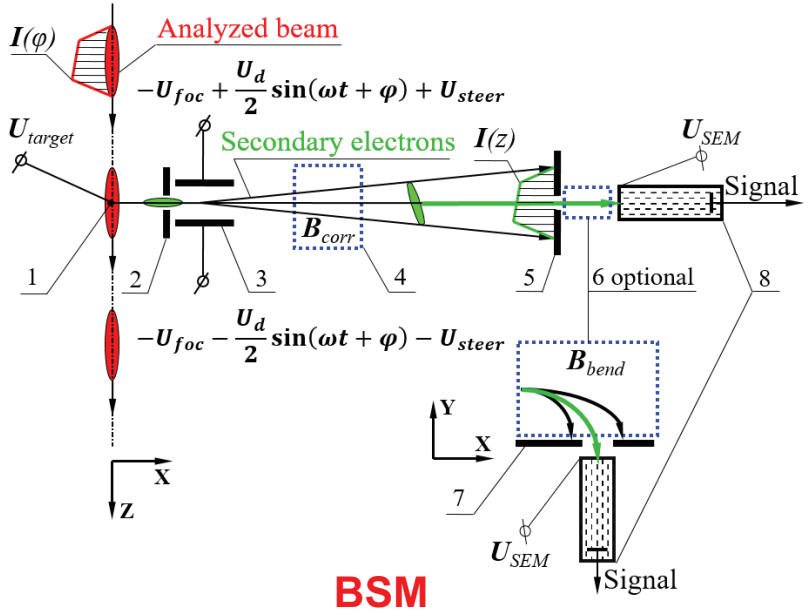
Bunch Shape Monitor

BLVD modification

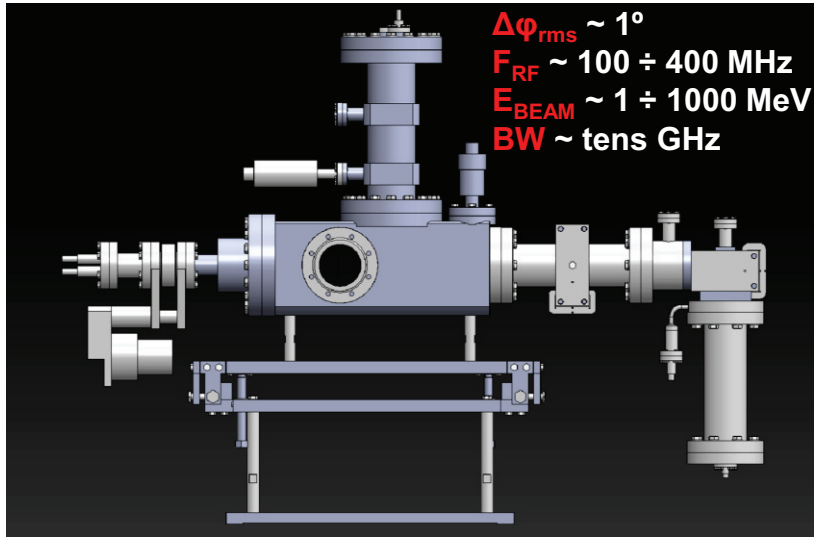


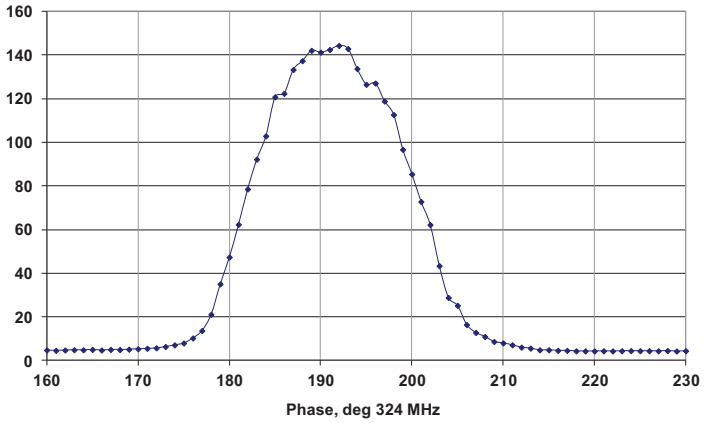
3D-BSM modification

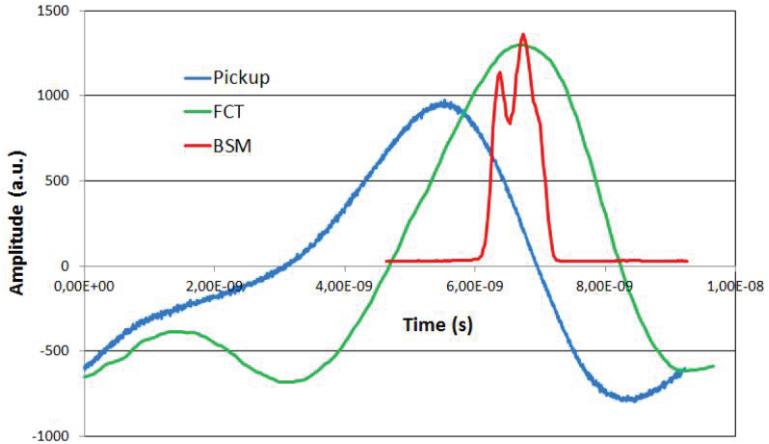




BSM

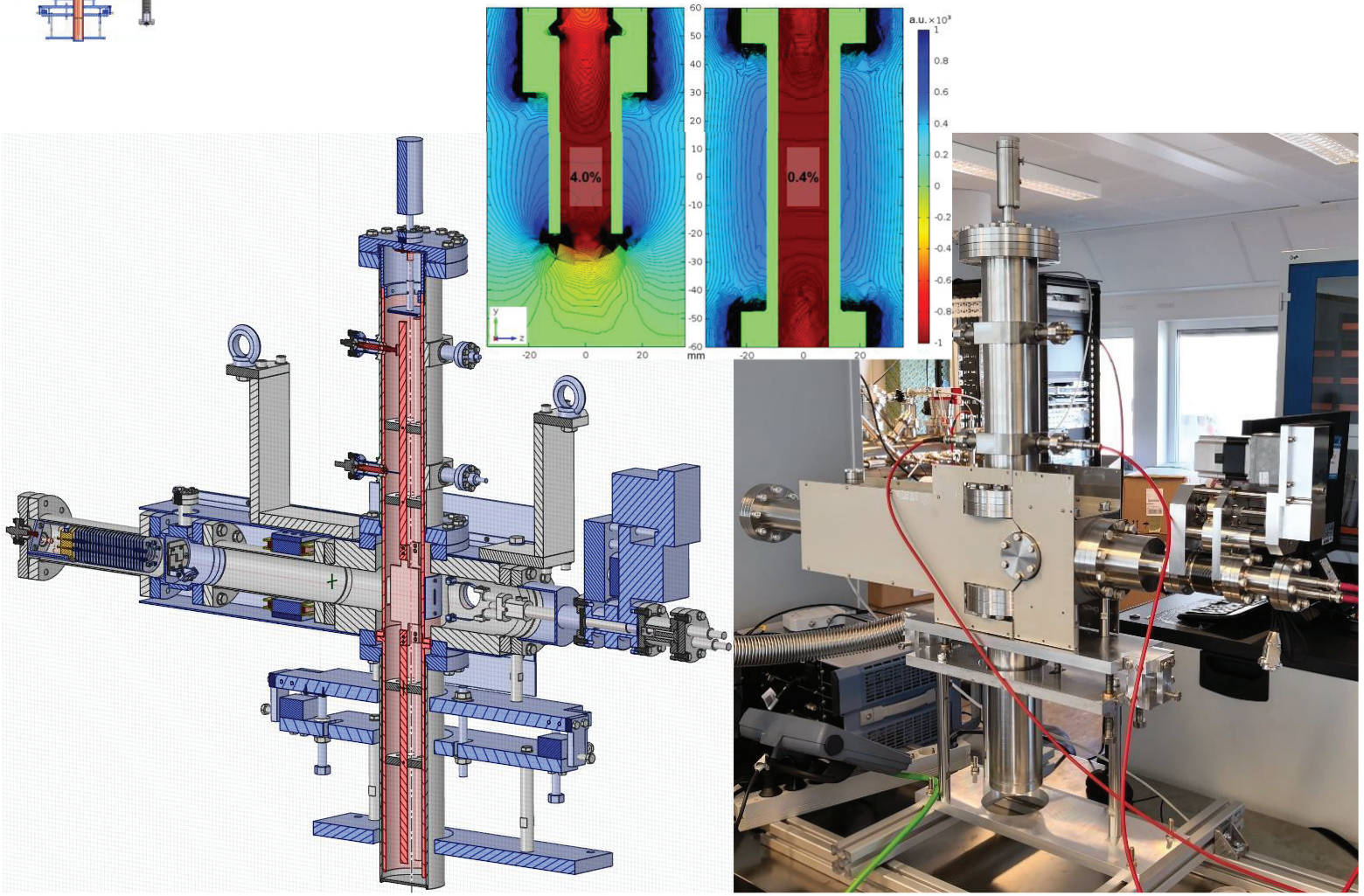




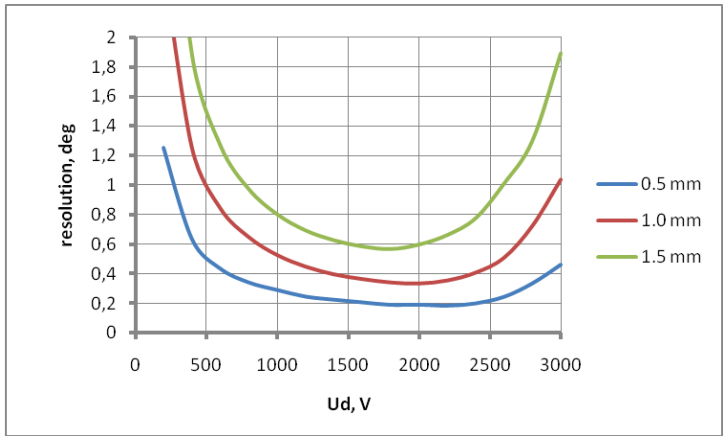


Bunch shapes of Ar^{9+} beam accelerated to 3.5 MeV/u at GSI CW-LINAC prototype. Courtesy of GSI (P. Forck), 2017.

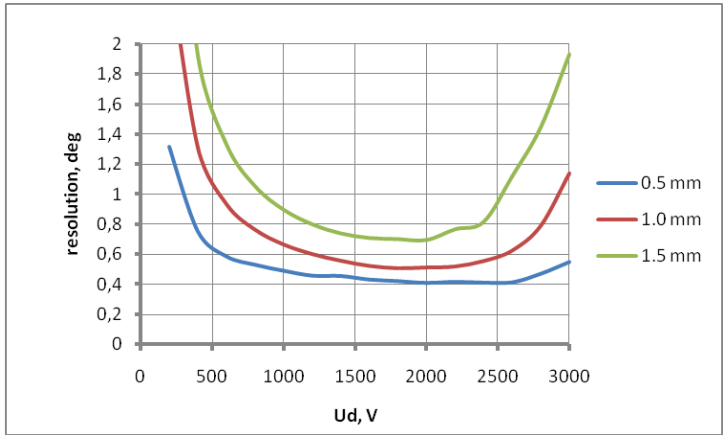
Symmetric RF-deflector



Calculated dependence of phase resolution on amplitude of deflecting voltage for different input collimators



without SEE time dispersion

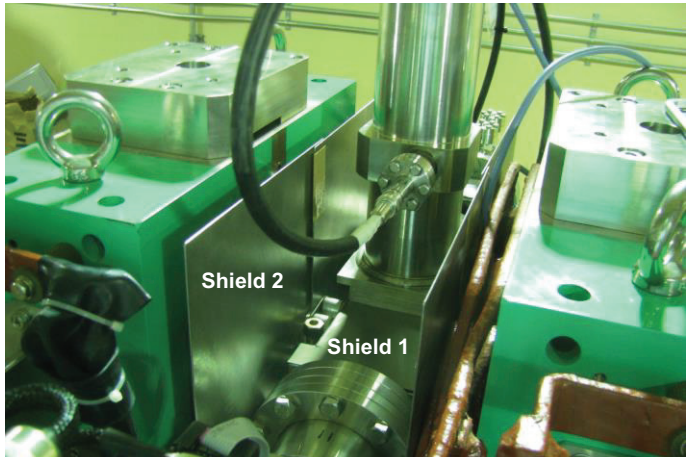


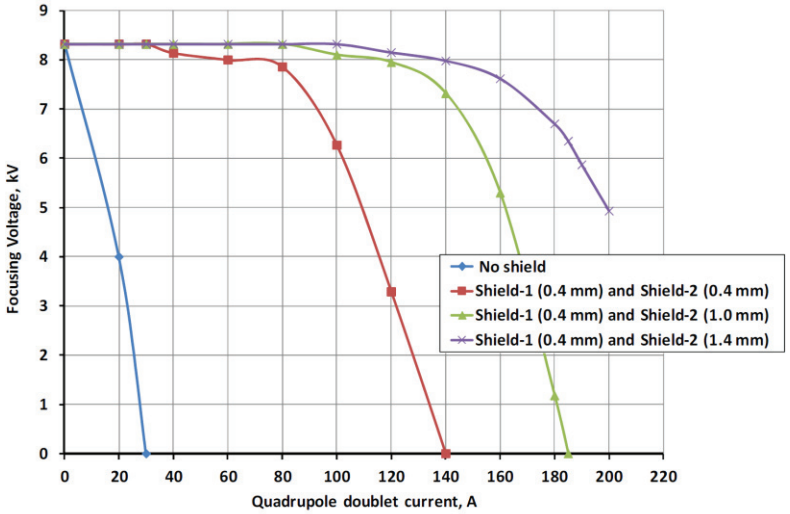
with SEE time dispersion

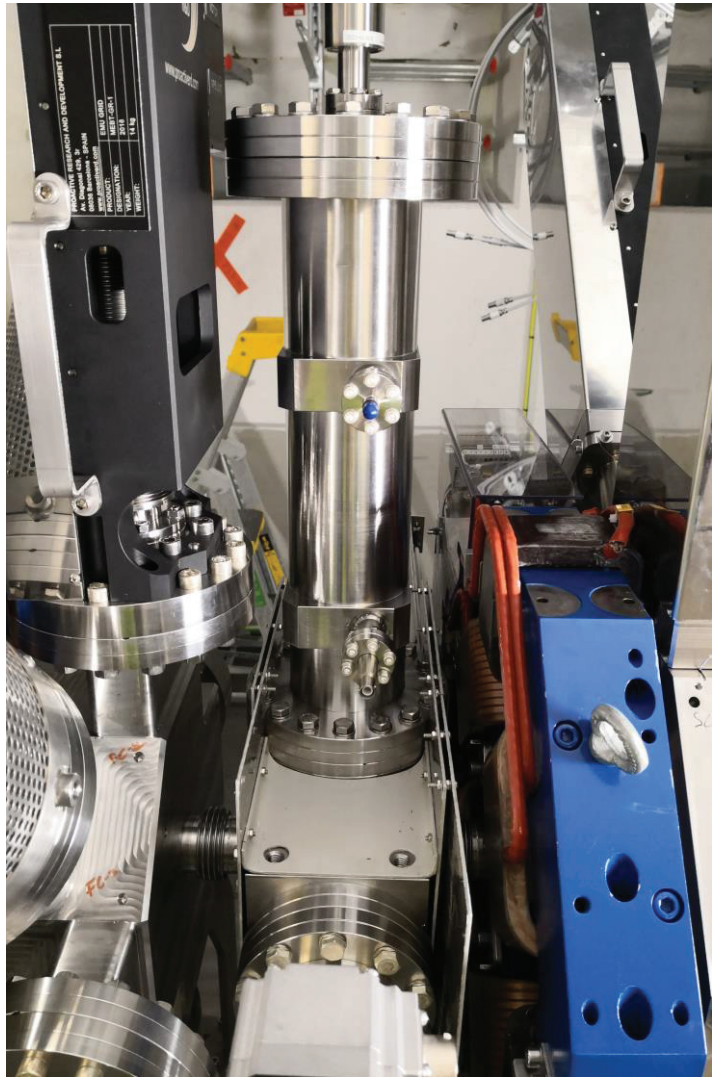
Estimated $\Delta\varphi_{rms}$ ~ 0.5° (352.2 MHz) ~ 4 ps

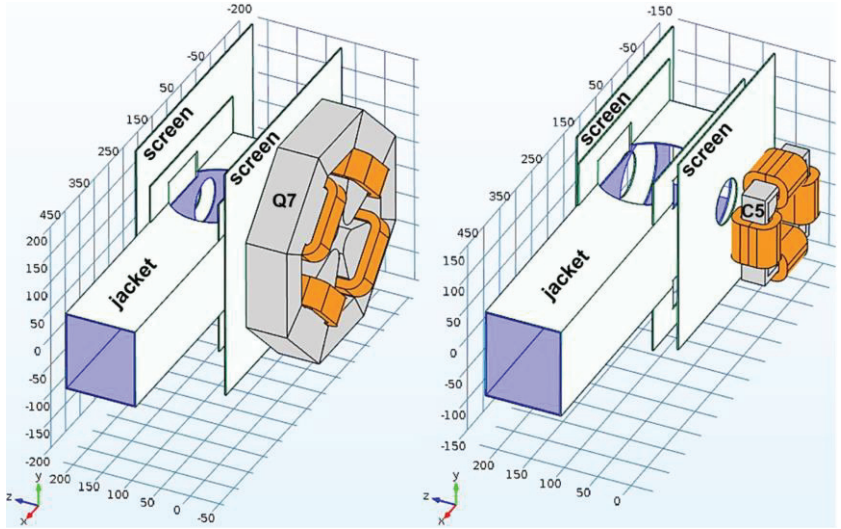
Main contribution to $\Delta\varphi_{rms}$ is $\Delta T_{SEE\ rms}$~3.5 ps (upper limit)

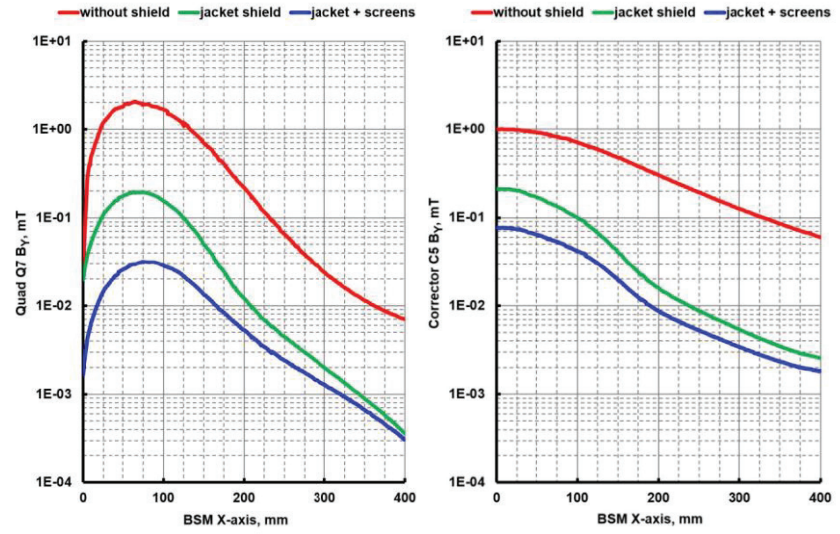
Magnetic shield

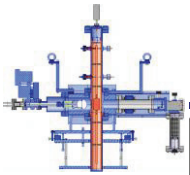




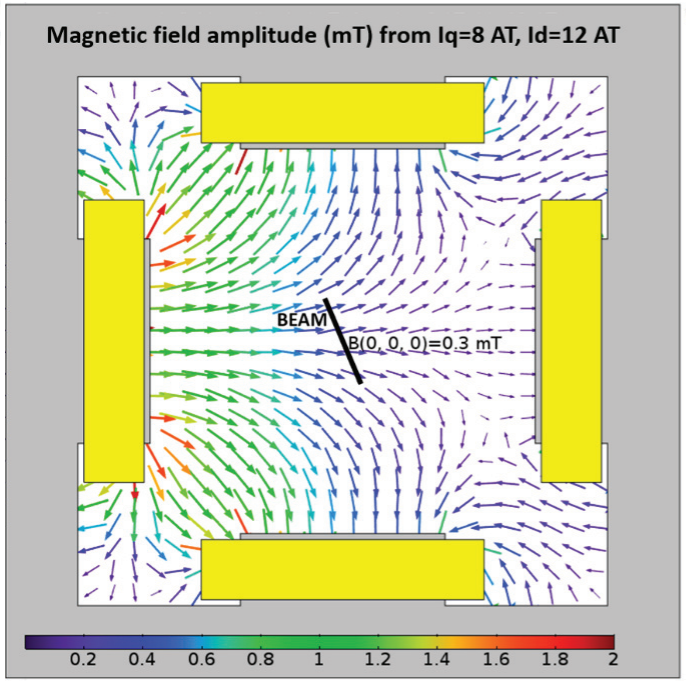




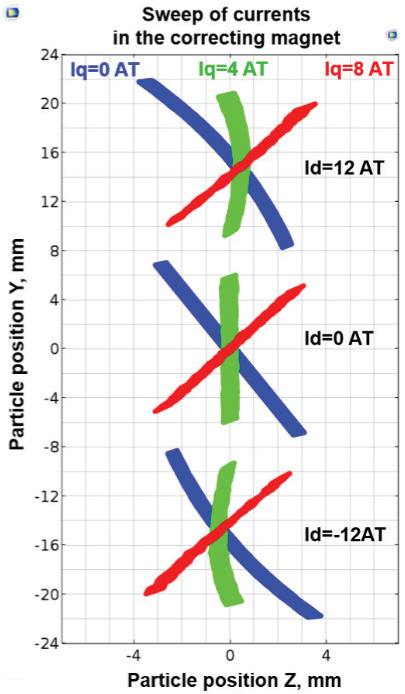




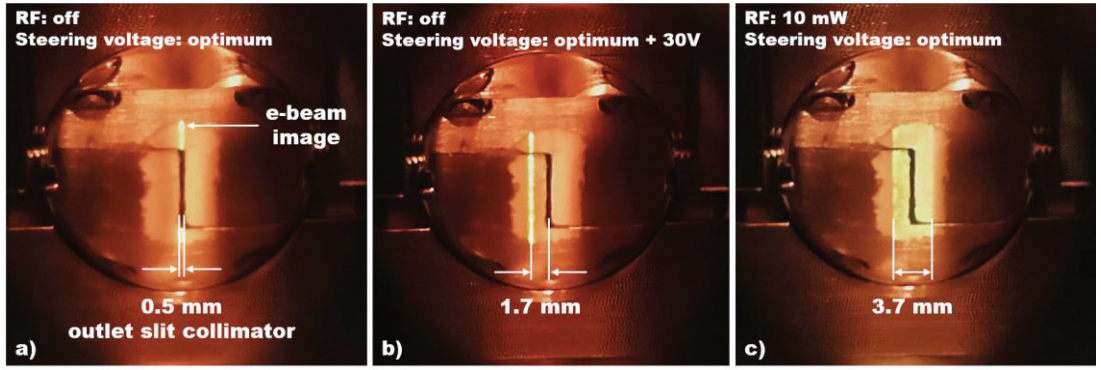
Magnetic correctors

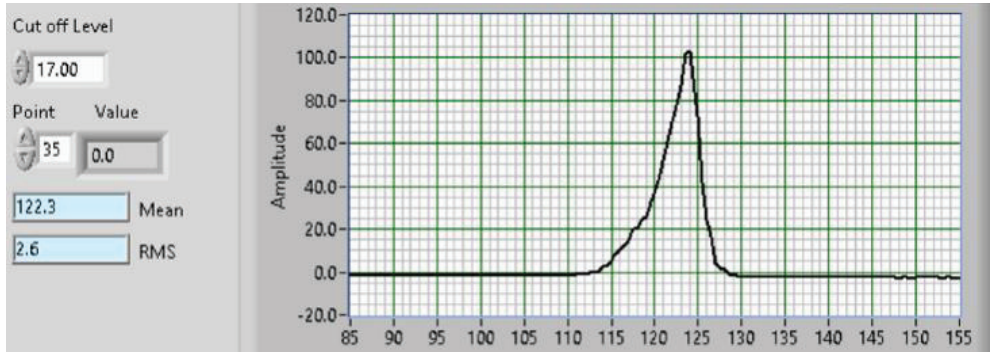


a)



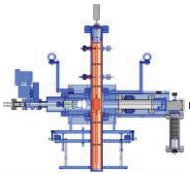
b)

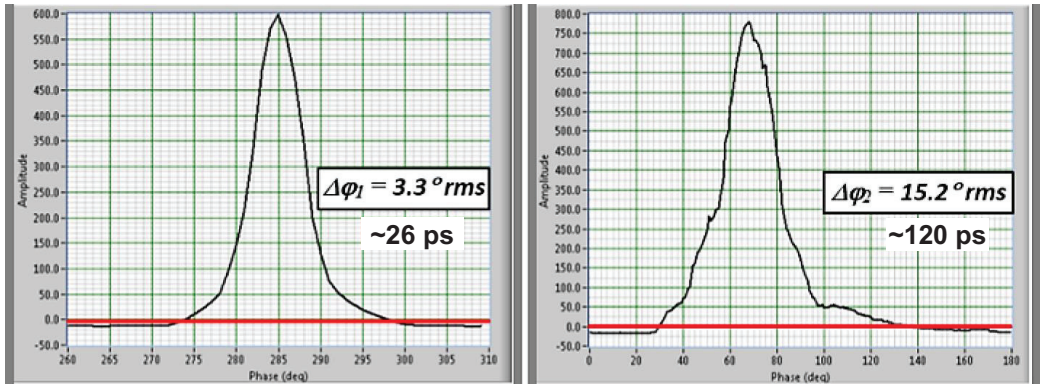




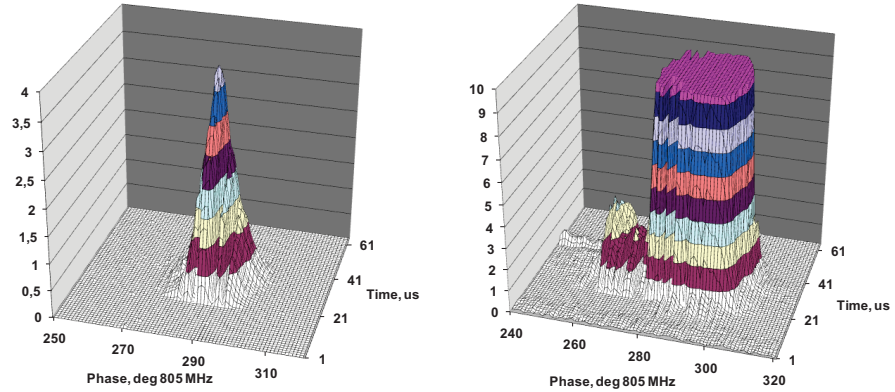
Bunch shape of 40Ar beam accelerated to 20 MeV/u
at FRIB MSU. Courtesy of FRIB (P. Ostroumov), 2019.

Basic measurements

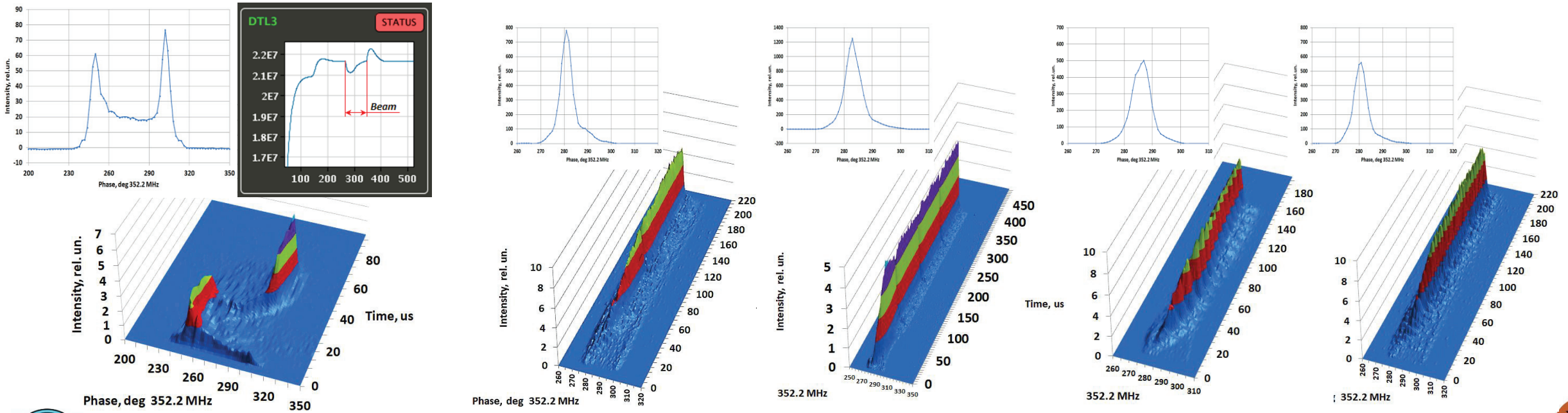




Bunch shape evolution of the H⁻ beam observed with the first BSM (left) at the exit of the LINAC4 and the second BSM (right) in the transfer line. Courtesy of CERN LINAC4 (J. Tan), 2018.

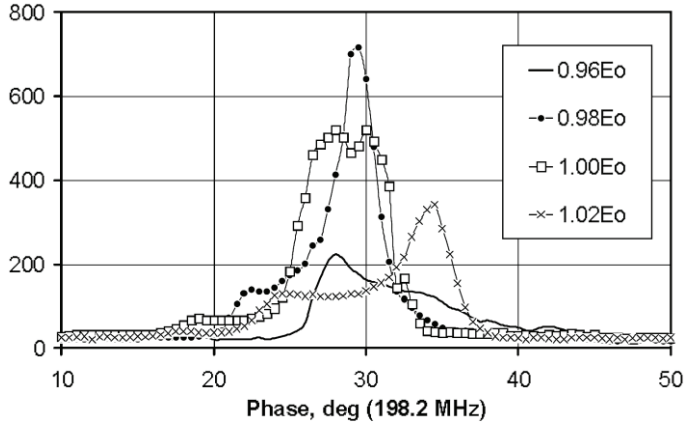


Measurements of **bunch longitudinal halo** in the first SNS CCL1 with the nominal SEM-gain (left) and 160x gain (right).

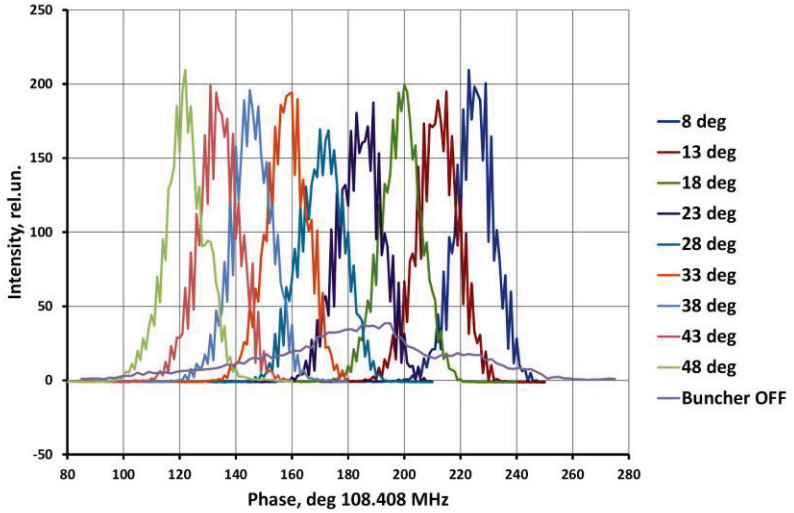


Behavior of **bunch shape in time** at the exit of the LINAC4 during commissioning process (first left) and at nominal routine parameters (others).

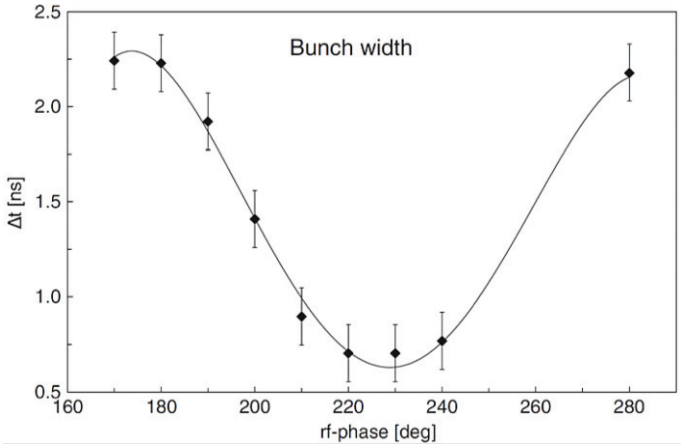
General diagnostic procedures



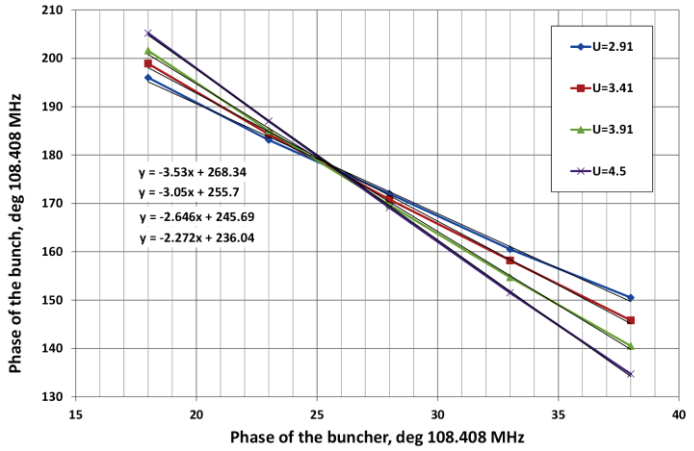
Bunch shapes of 20 MeV proton beam at different amplitudes of accelerated harmonic in DTL Tank 1 of INR RAS linac during commissioning process.



Bunch shapes for different phases of GSI R1-buncher (buncher voltage U=3.41 a.u.).

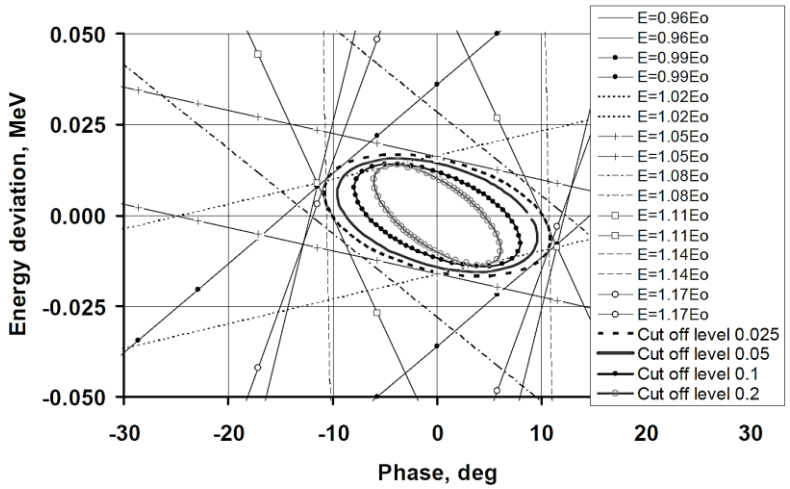


Phase tune with corresponding bunch length (FWHM) of GSI CW-LINAC prototype at 3.5 MV/m for Ar^{9+} ions.
Courtesy of GSI (P. Forck), 2017.



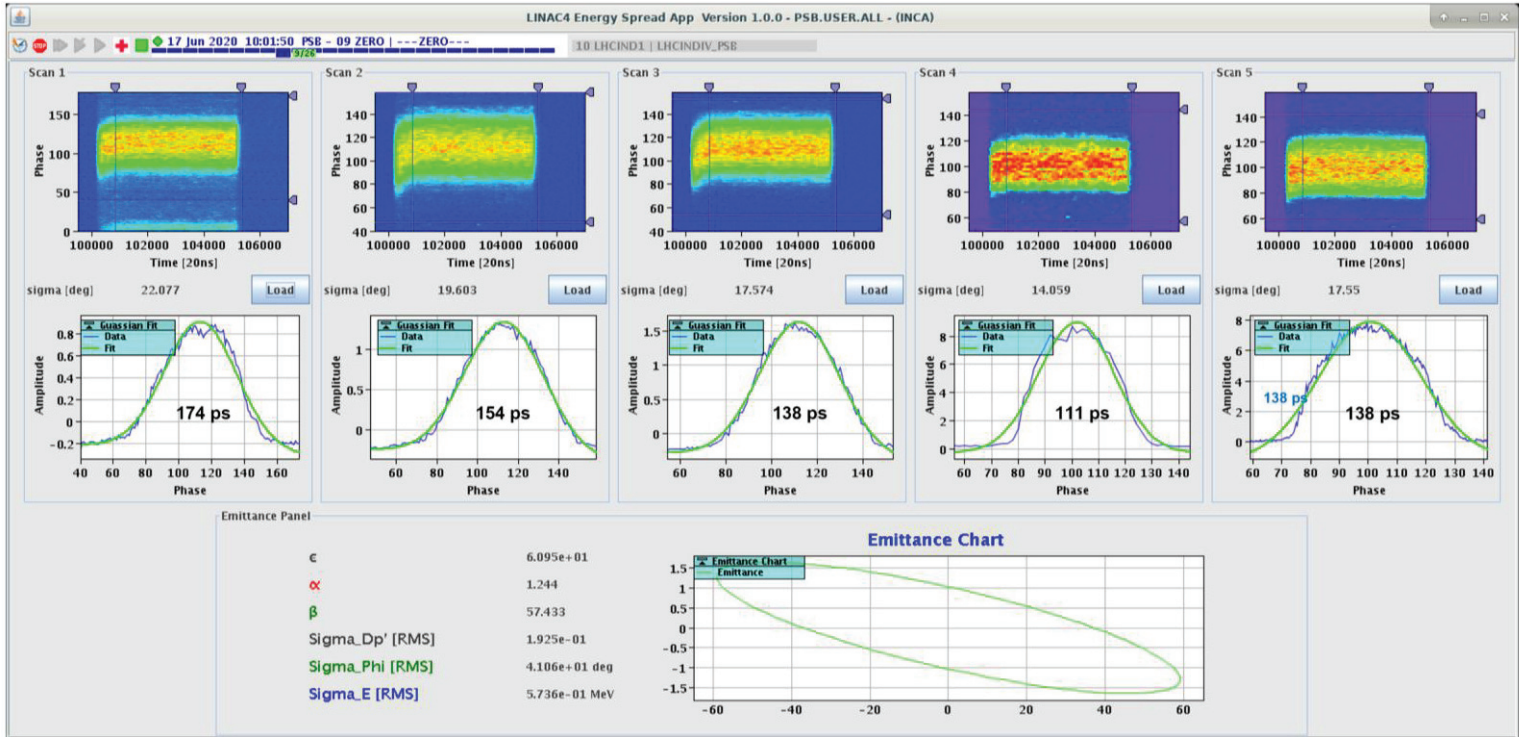
Bunch average phase vs. GSI R1-buncher phase for different buncher voltages.

Advanced diagnostic procedures

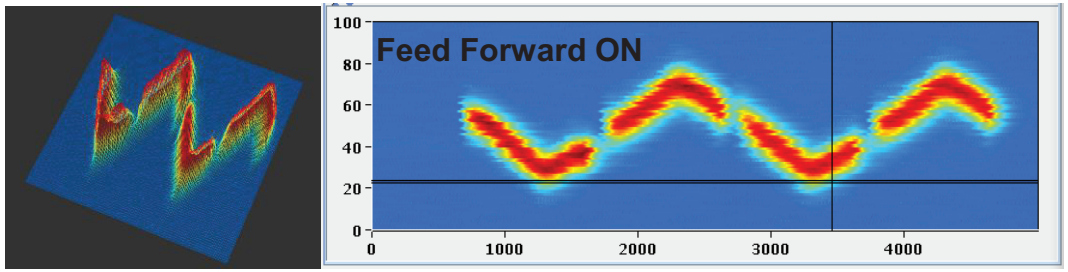


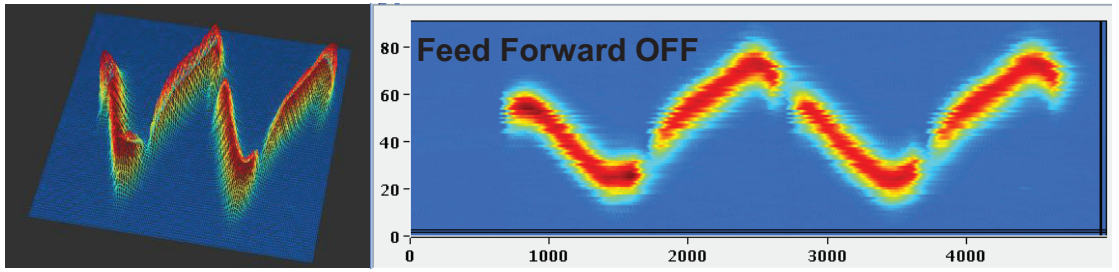
Longitudinal phase ellipses at the entrance of SNS DTL Tank 1 for different cut off levels. (The tangents are shown for 0.025 cut off level).

Longitudinal phase ellipse at the entrance of PS Booster. Courtesy of CERN LINAC4 (J. Tan), 2021.



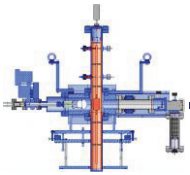
Observation of energy ramping procedure
with a beam for 4 rings of PS Booster (20 μs per ring) at CERN LINAC4





International experience

Year	LINAC	Beam commissioning	Quantity
1988	INR RAS	H^+ (20, 100 MeV)	1 BSM
1993	SSC RFQ	H^- (2.5 MeV)	1 BSM
1994	CERN LINAC3	Pb^{27+}(0.25, 4.2 MeV/u)	1 BLVD
1996	CERN LINAC2	H^+ (50 MeV)	1 3D-BSM
1996	JHP RFQ	H^- (3 MeV)	1 BLVD
1997	DESY	H^- (10, 30, 50 MeV)	2 BSMs + 1 BLVD
1997	INR RAS	H^+ (160 MeV)	1 BLVD
1999-2000	CERN LINAC2	H^+ (10, 30 MeV)	2 BSMs
2003-2010	SNS ORNL	H^- (7.5, ~90, ~180, ~1000 MeV)	8 BSMs
2012-2016	CERN LINAC4	H^- (3÷160 MeV)	2 BSMs
2012	J-PARC	H^- (~200 MeV)	3 BSMs
2016	LANSCE	H^+, H^- (0.75, ~70 MeV)	2 BSMs
2016	GSI-FAIR	Ar^{9+}(3.5 MeV/u)	1 BSM
2019	FRIB	Ar^{9+}(20 MeV/u)	1 BSM
2021	GSI-FAIR	Ar^{9+}(1.4÷7 MeV/u), H^+ (3÷70 MeV)	2 BSMs
2021 ???	ESS	H^+ (3.6, 90 MeV)	2 BSMs
2022	MYRRHA	H^+ (1.5, 5.9 MeV)	1 BSM



Conclusions & lessons learned

- **Wide range of ion type, beam energy, beam intensity, RF frequency**
  Each BSM differs from others (>30) by a set of individual technical solutions: geometry, RF deflector & electronics, e-beam dynamics.

- **Resolution ~0.5º (equivalent bandwidth > 100 GHz)**
  Users want 0.1º (~ 1 ps), but it seems that we have achieved the fundamental limit for bunch shape measurements with secondary electrons.

- **Space charge effects for currents > 10 mA**
  These effects can be reliably simulated and don't decrease resolution worse than ~2 degrees at tens mA.

- **Secondary electrons vs. beam electromagnetic field**
  The key is bandwidth. It demands a localization of space region, where the bunch shape information transfer occurs.

- **Physical target heating limits**
  BSM faces the same beam intensity limits as wire scanners, so transparent device – a challenge for the current decade.