Longitudinal Cooling Force Measurements at CELSIUS

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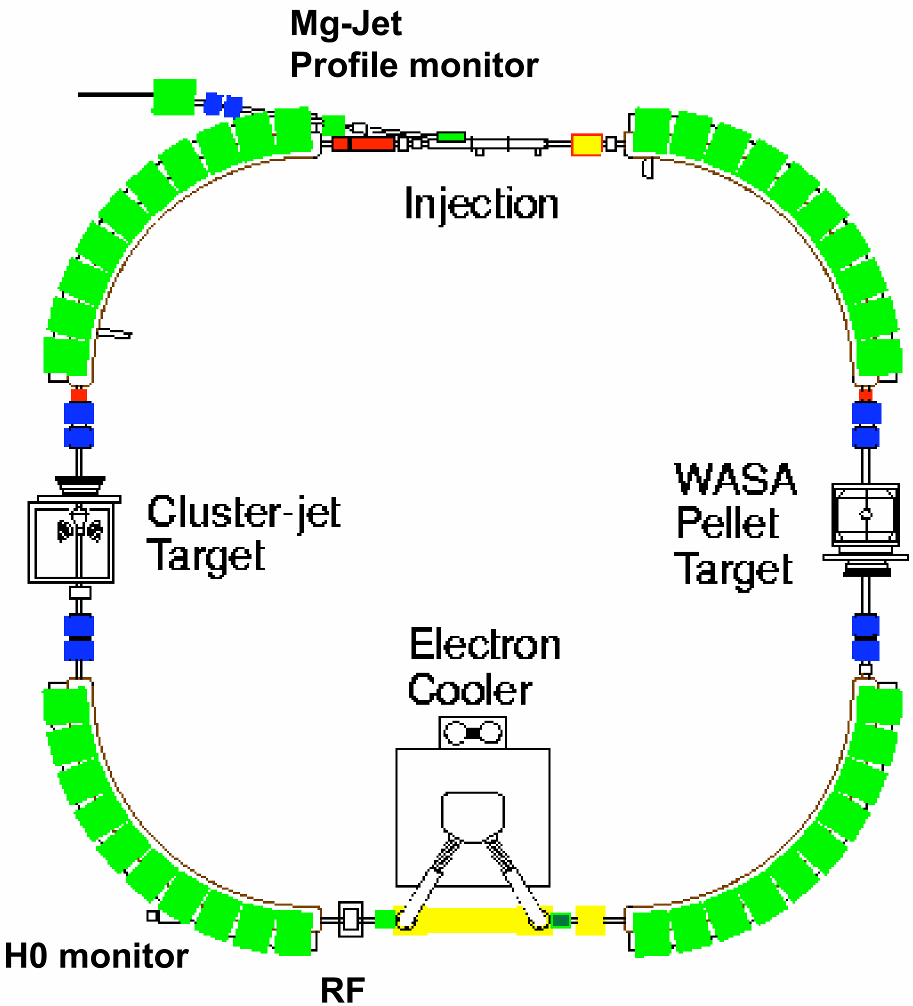
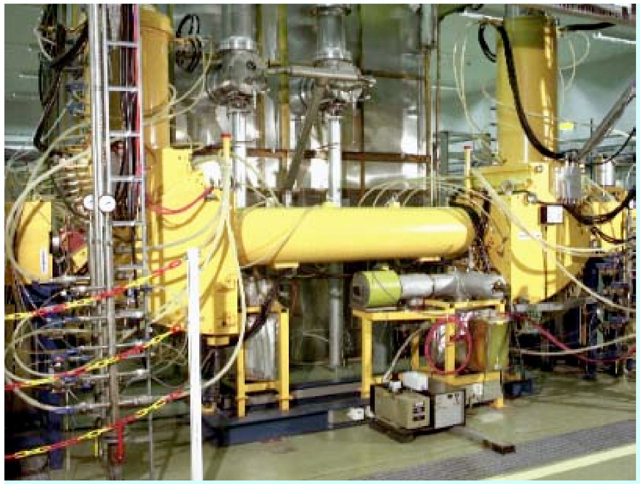
The CELSIUS Ring



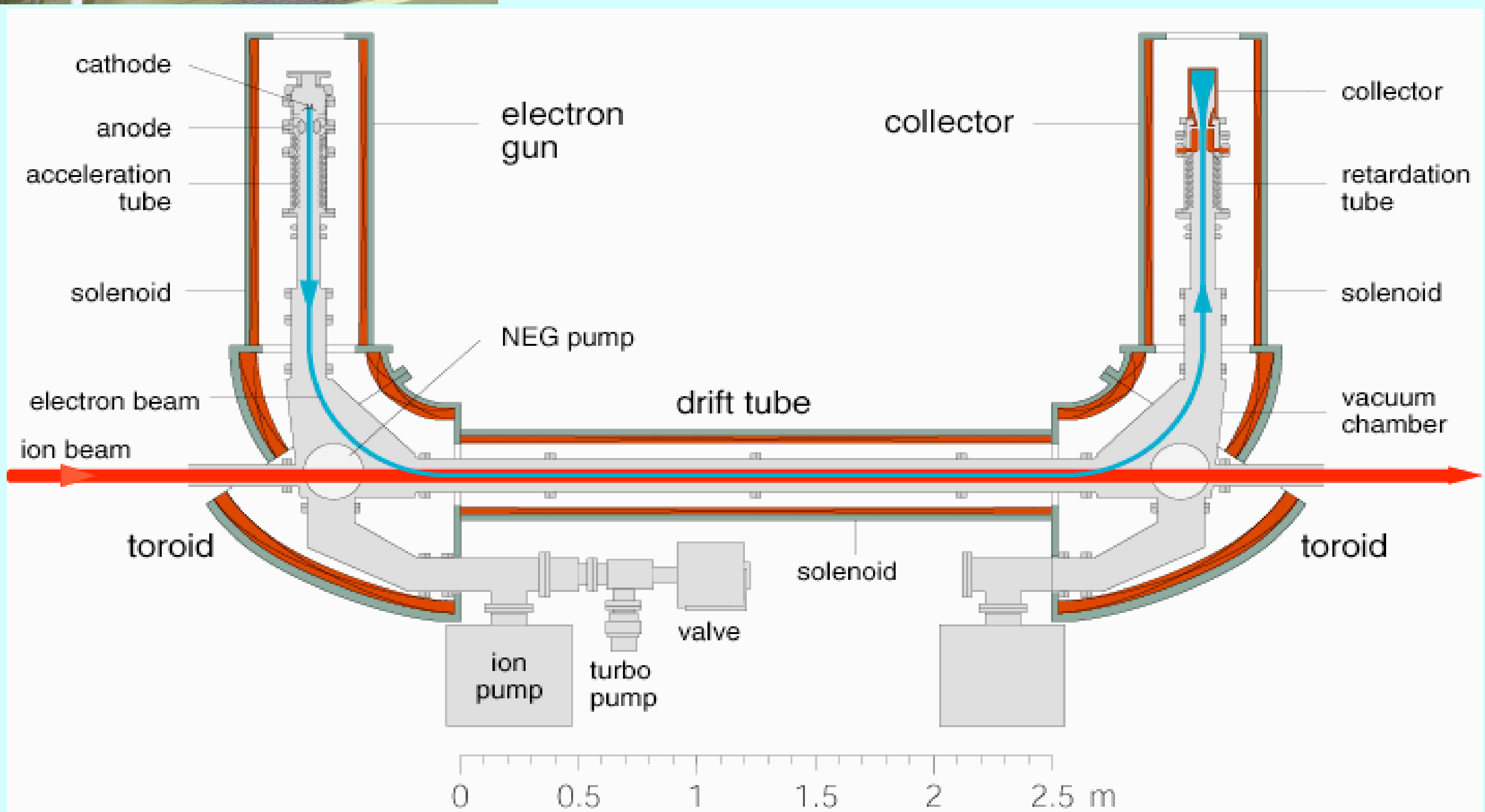
- Last CELSIUS run in June 2005
  Now dismantled
- WASA to COSY, Jülich

Circumference	81.8 m
Length of cooling and injection straight sections	9.6 m
Length of target straight sections	9.3 m
Bending radius	7.0 m
Maximum rigidity	7.0 Tm
Maximum kinetic energy (protons)	1.36 GeV
Maximum kinetic energy per nucleon for ions with *Q/A* = 1/2	470 MeV



CELSIUS electron cooler

Electron energy	300 keV
Cathode diameter	20 mm
Perveance	0.45 uP
Beam current	2 A
Magnetic field	0.17 T
Interaction length	2.5 m
Collection inefficiency	<1e-4
Vacuum pressure	<1e-10 mbar



Background: Need for accurate cooling force description

- Important to have a good description of the cooling force. Different descriptions predict different force; Parkhomchuk, Derbenev-Skrinsky-Meshkov.

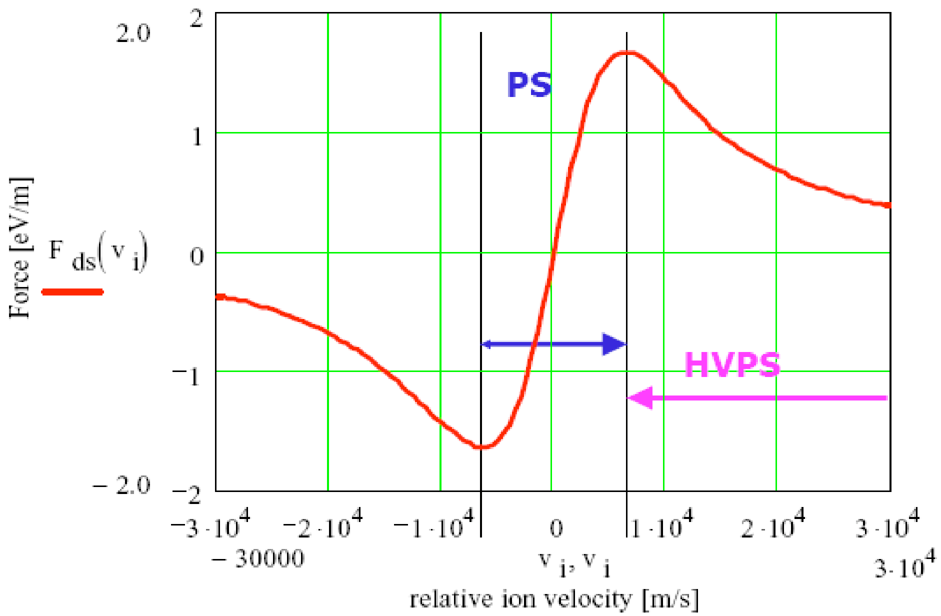
- Especially important in high energy cooling projects HESR, RHIC, where cooling down times can be in the order of 1000 s.

- Objectives:

    - To make accurate measurements of the cooling force to provide data needed for benchmarking.

    - To measure dependencies of the cooling force of different parameters such as electron current and magnetic field.

Measurement methods for longitudinal cooling force



- PS-Phase shift in linear region

- HVPS, voltage step method - also outside linear region

Phase shift measurements presented here.
Accurate in the linear regime

Phase shift method

• Both RF and and electron cooling is applied

• The idea is to measure the phase-shift, Δϕ between RF voltage and beam at equilibrium between the cooler force and the force from the RF cavity.

• The cooling force is then given by: $F_{\|} = Z\hat{U}_{RF}\sin(\Delta\phi)$ eV / turn

where $\hat{U}_{RF}$ is the RF voltage and Δϕ the phase shift

• Relative velocity difference between protons/ions and electrons in co-moving, beam frame

$$v_{\|}^{*} = \beta c\frac{\Delta p}{p} = \frac{\beta c}{\eta_p}\frac{\Delta f}{f} = \frac{C}{\eta_p}\cdot\Delta f$$

C = Circumference; η_p = slip factor; f = rf frequency

Phase shift measurements

• Measurements were done at injection energy, 48 MeV protons, Ucool = 26 kV.

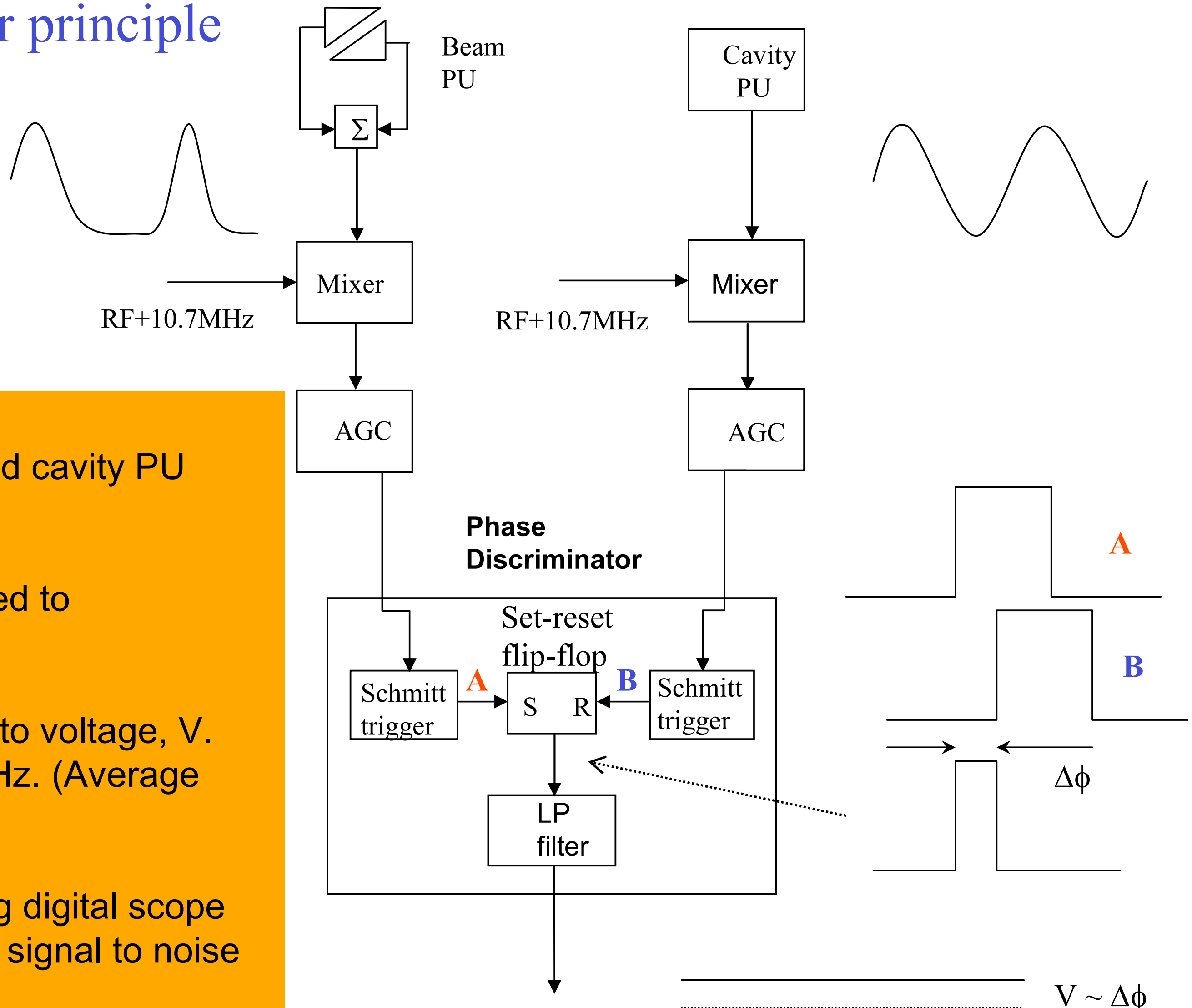
• Measurements were done with a bunched beam, using relatively low RF voltage ~10V.

• The phase shift was measured with a phase discriminator with integration time of 2 s to get a good signal to noise ratio. (Earlier measurements at CELSIUS were done with a network analyser)

• Changing the RF frequency instead of cooler voltage allowed us to make measurements in fine steps in relative velocity (1 Hz of 1129 kHz). Typical step 10 Hz.

• Similar technique has been used at IUCF and TSR, Heidelberg for example.

Phase discriminator principle

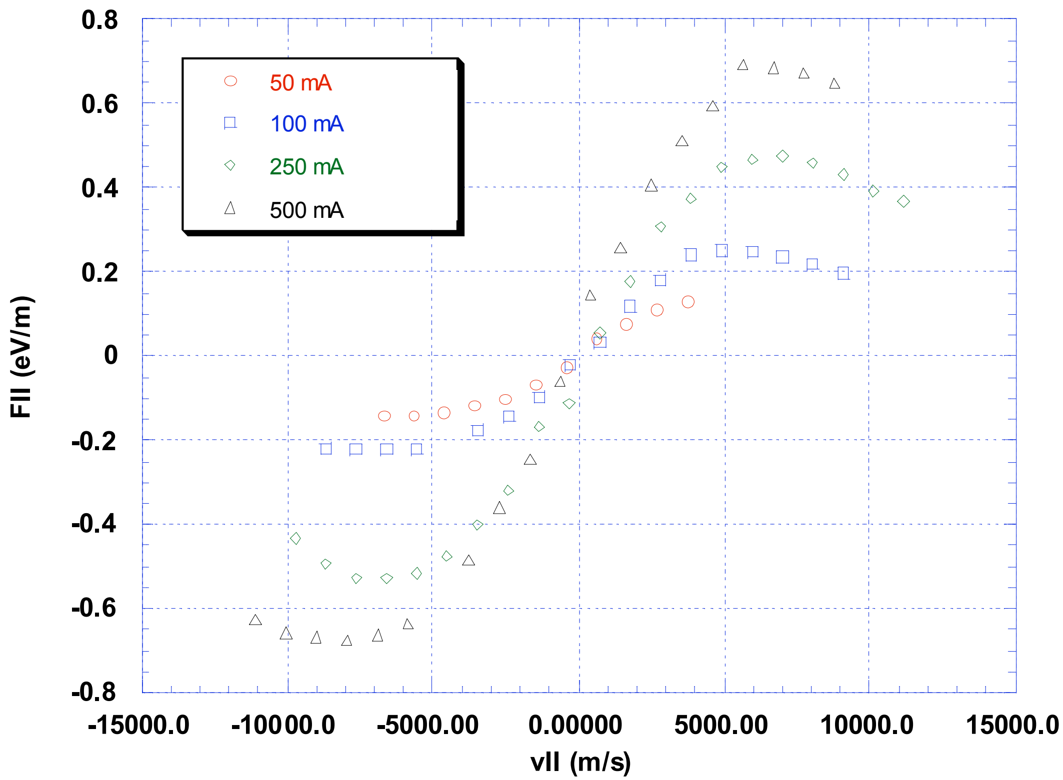


- Signals from beam PU and cavity PU are pulse shaped
- Phase difference converted to pulse length in flip-flop
- Low pass filter to convert to voltage, V. Filter cut-off frequency 15 Hz. (Average approximately 20 ms.)
- Additional averaging using digital scope (Le Croy) 2 s to get a good signal to noise ratio.

Summary of measurements at CELSIUS December 2004 and March 2005.

1. Longitudinal cooling force measurements at standard cooler settings.
2. Cooling force measurements at different alignment angles between electron and ion beams.
3. Influence of the imperfection of the longitudinal magnetic field.
4. Cooling force measurements at different degrees of magnetisation.
5. Transient cooling measurements, longitudinal and transverse.

Examples of results - 1. Standard cooler settings

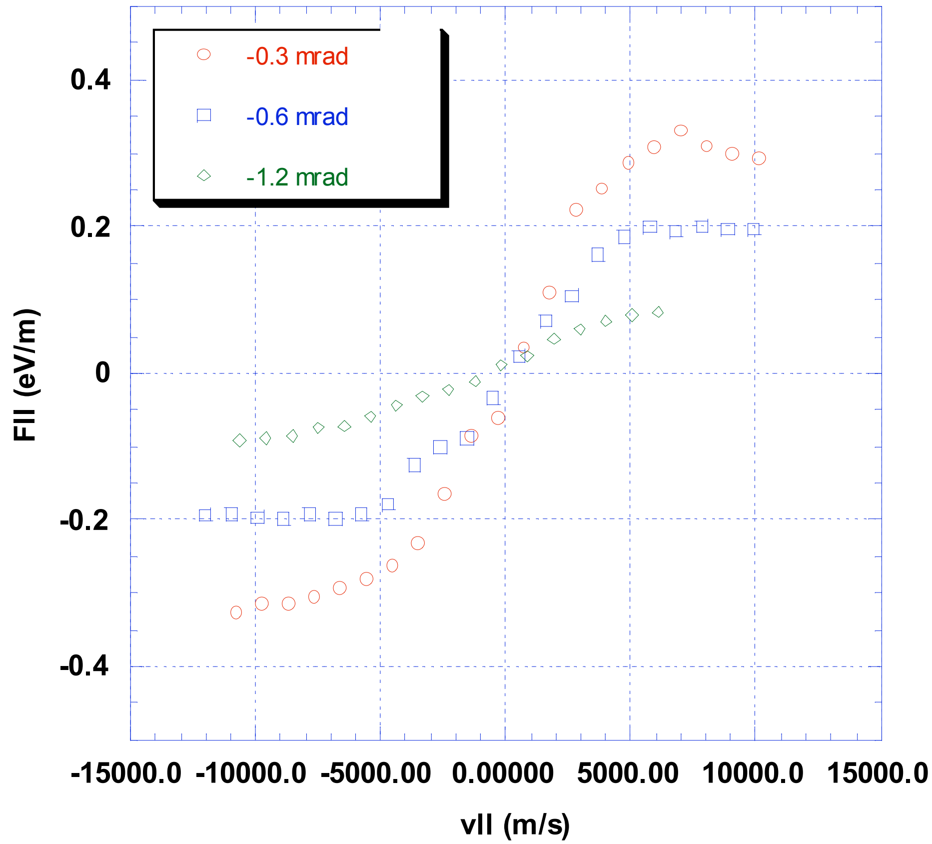


B = 0.1 T
48 MeV protons

Different electron currents,
Ie = 50, 100, 250 and 500 mA

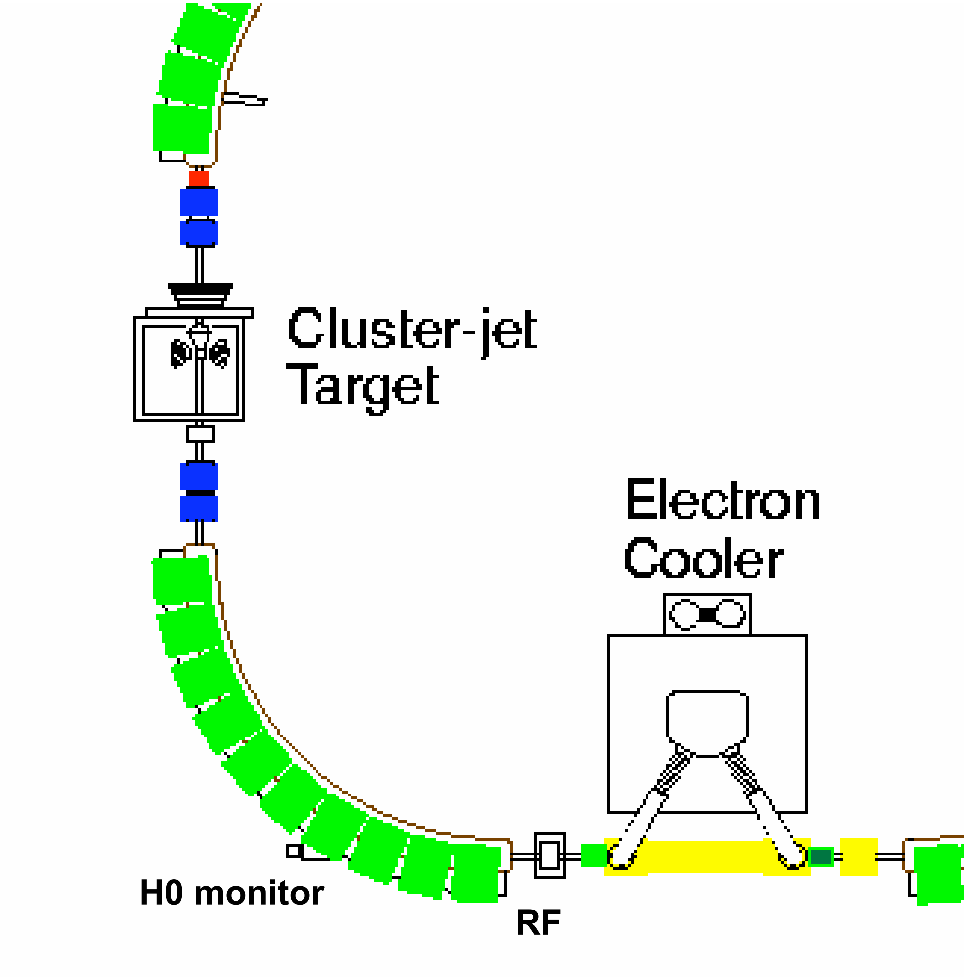
Ip = 40 μA

Examples of results - 2. Different alignment angles



Different misalignments horizontally between ion and electron beam; 0.3, 0.6, 1.2 mrad.
Calibration was carried out using H0 monitor.
Idea – to introduce a controlled "magnetic field error"

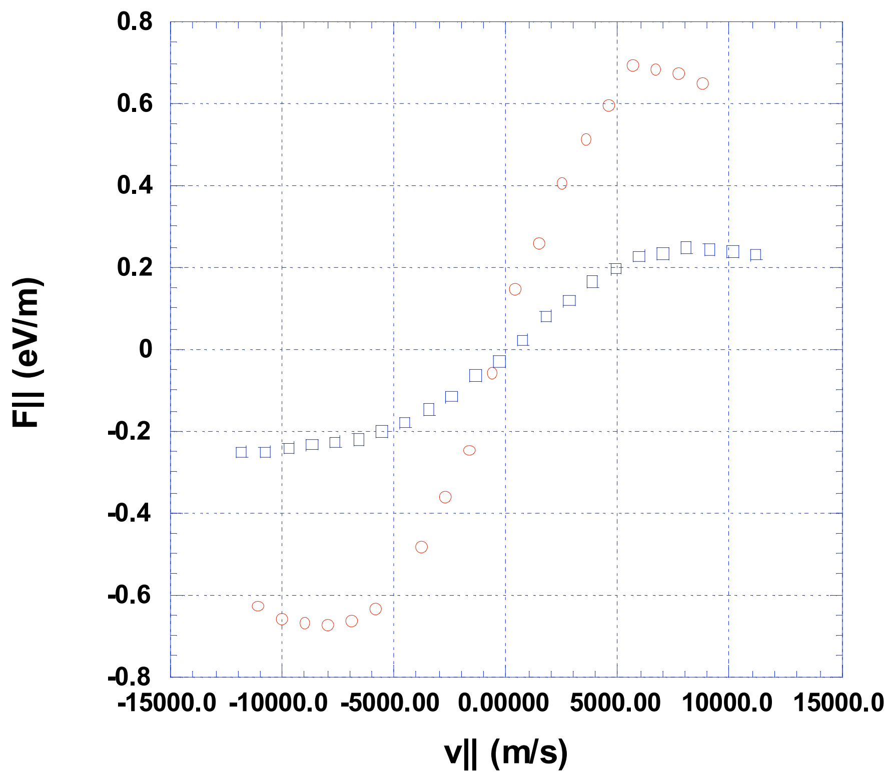
H0 Calibration



Calibration of the different misalignment angles were done by looking at the H0 profile 9 m from the center of the cooler.

A 1 mrad misalignment thus corresponds to a movement at the H0 of 9 mm

Examples of results – 3. Imperfection of magnetic field



Measurement at two different errors of the magnetic field in cooling section.

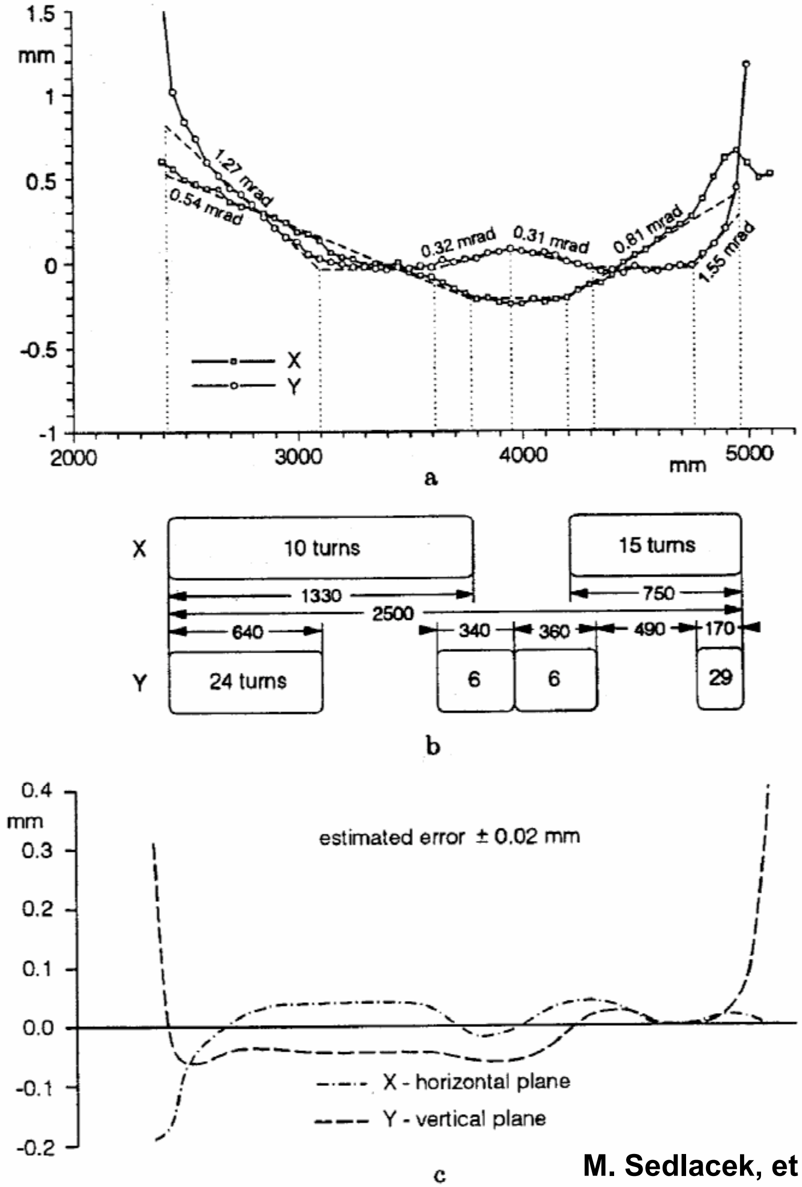
○ DTCOR on - $\theta_e \approx 0.2$ mrad
Correction coils on

□ DTCOR off – $\theta_e \approx 1$ mrad
Correction coils off

θ_e, rms misalignment angle.

Comparison to VORPAL simulations
See We. talk by D. Bruhwiler

Measured field error



Error before Correction ~1 mrad DTCOR off

Correction coils

Remaining error ~0.2 mrad DTCOR on

Measurements done with a pencil electron beam of 0.05 mm and a flourescence screen

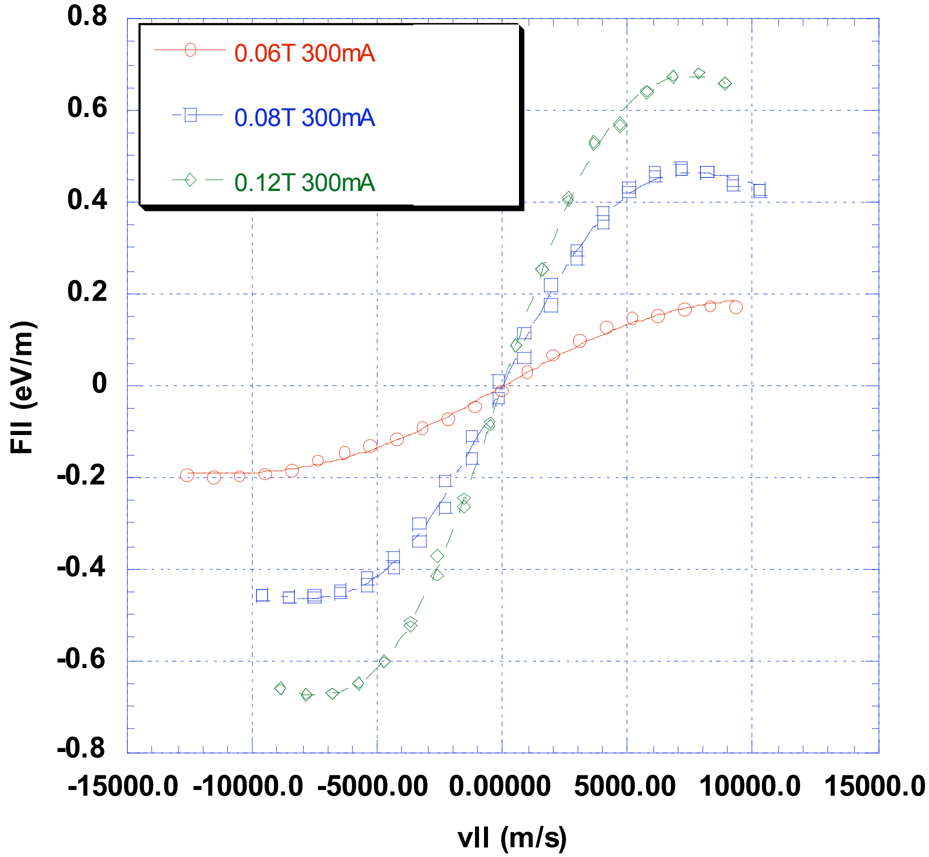
M. Sedlacek, et al. "Design and construction of the Celsius electron cooler" Montreux, 1993

Examples of results - 4. Different degree of magnetisation

Fit to parametrized V. Parkhomchuk cooling force

C and Veff are fitting parameters

$$\vec{F} = C \cdot 4 \cdot \left(\frac{Z \cdot q^2}{4\pi\varepsilon_0} \right)^2 \frac{n_e}{m_e} \cdot \frac{\vec{V}_i}{\left(V_i^2 + v_{eff}^2\right)^{3/2}} \ln\left(1 + \frac{b_{max}}{b_{min} + r_L}\right)$$

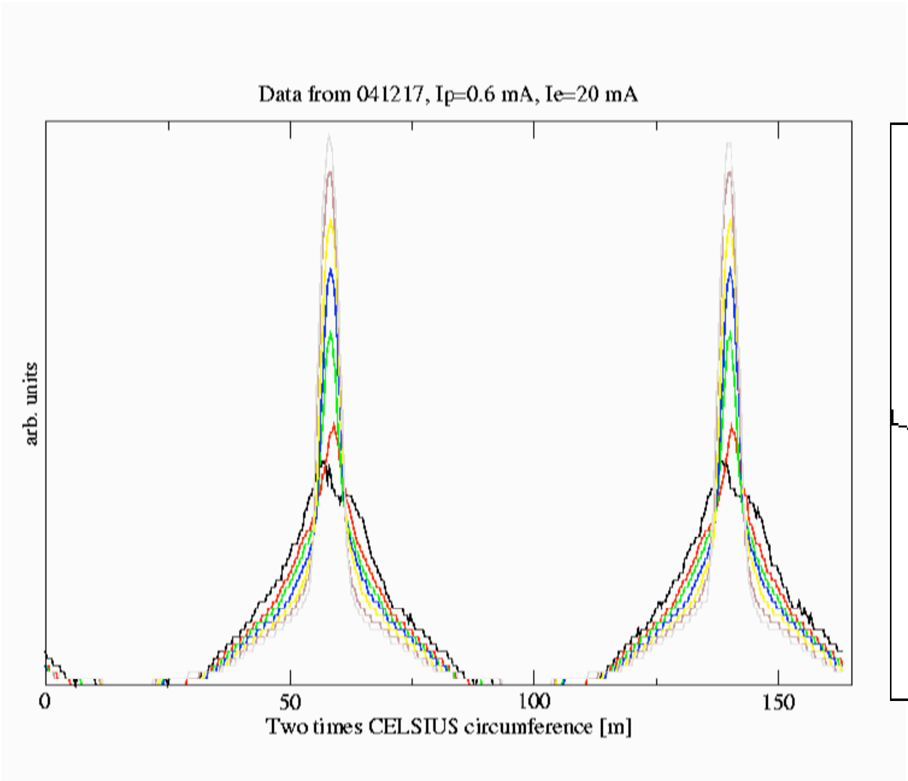


- B = 0.06 T, 0.08 T, 0.12 T, Ie = 300 mA
- Measure at different regimes of magnetization varying B and Ie; Different values of the logarithmic term. Idea was to go also into the non-magnetised regime.
- Increase of cooling force with magnetic field; log increases due to smaller Larmor radius r_L.
- Magnetic field corrections optimised at 0.12 T. Field error could be larger at smaller fields

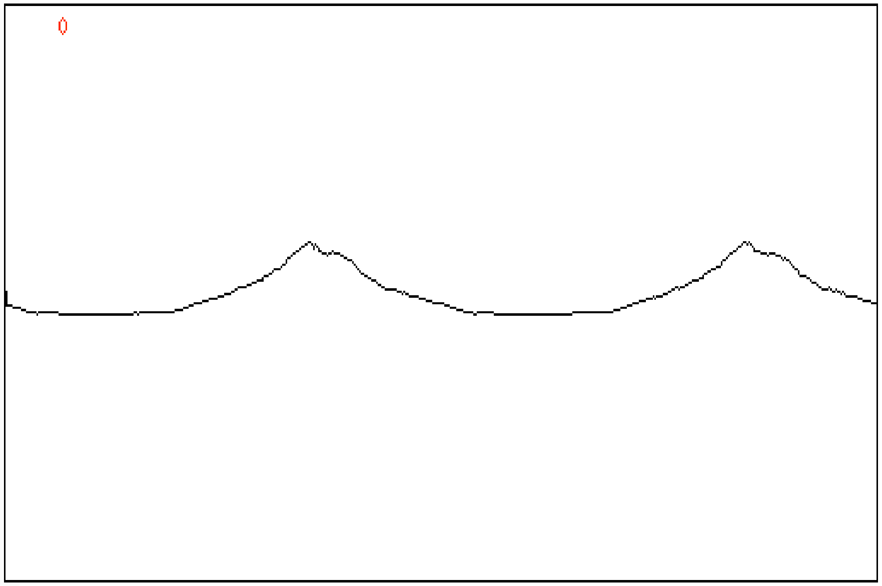
See talk by A. Fedotov for more details about comparison to calculations

Transient cooling measurements

Longitudinal profiles.



0.75 s between profiles. Total 4.5 s

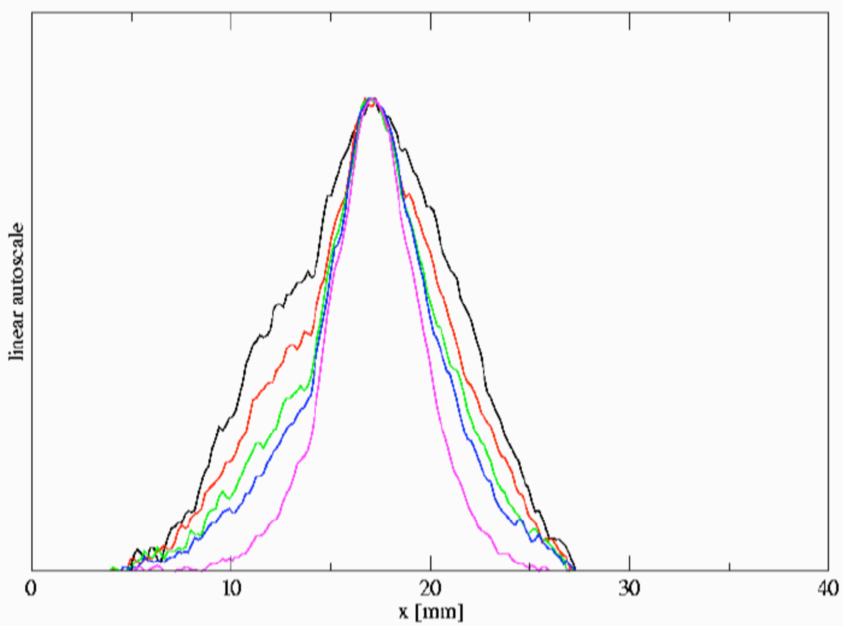


15 ms between frames (total 4.5 s)

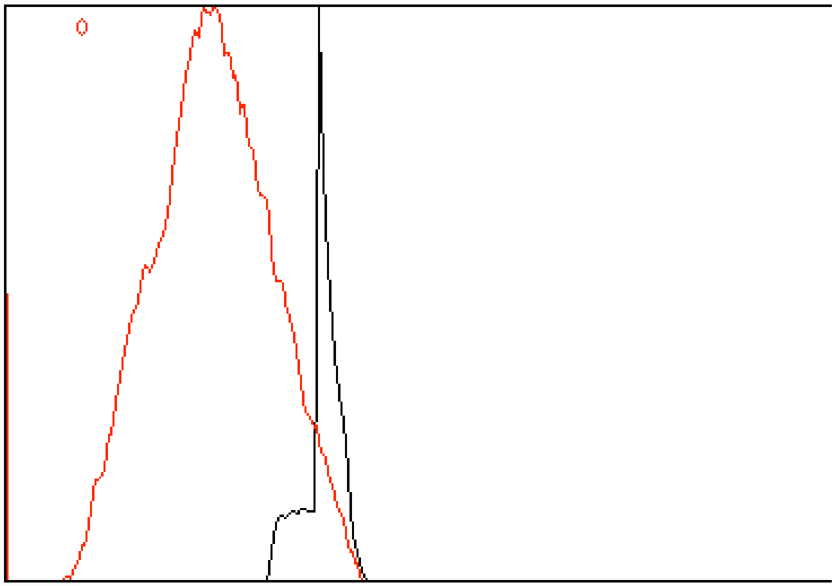
Cooling of core vs. tails.
Ie = 20 mA, Ip = 0.6 mA, Np = $3.3 \cdot 10^9$
Can be used in comparisons of calculations with IBS models.

Transient cooling measurements

Transverse Mg-Jet profiles



0.3 s between profiles (total 1.5 s)



Time between frames 0.3 s. Total ~60 s

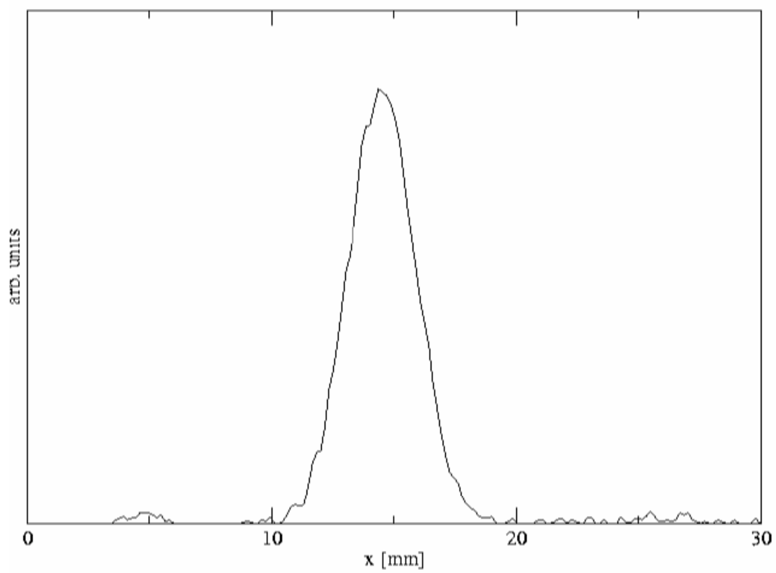
Cooling of core vs . tails

Electron current 10 mA and proton current 0.3 mA, Np = $1.7 \cdot 10^9$.

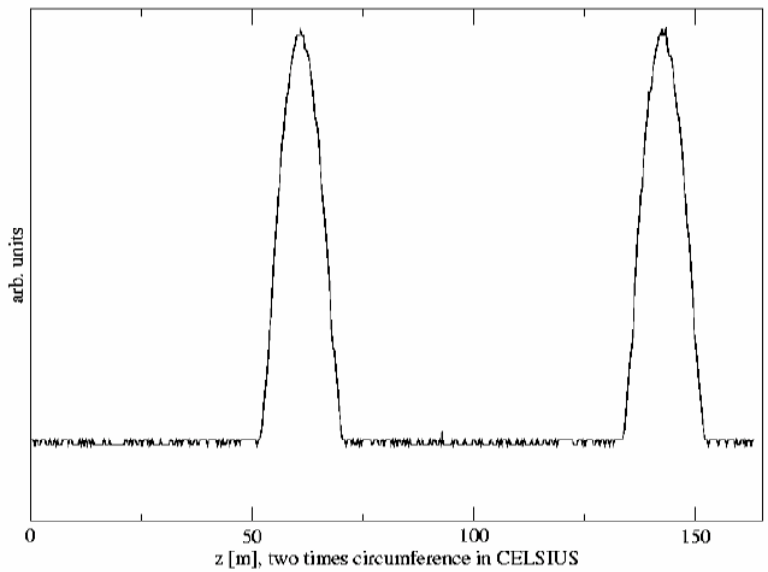
Can be used in comparisons of calculations with IBS models.

Beam characterisation

Mg-Jet profiles for emittance determination



Longitudinal bunch length for momentum spread determination (2 turns)



	MGPM		SHARC	
	fwhm/pixel	fwhm/mm	fwhm/pixel	rms dp/p [1e-5]
u5	12-15	2.0-2.6	37/37	5.6/5.6
u6	10-14	1.7-2.4	26/29	3.9/4.4
u8	17-19	2.9-3.2	39/39	5.9/5.9
u10	11-13	1.9-2.2	34/26	5.2/3.9
u13	12	2.0	41/40	6.2/6.1
u14	11	1.9	37/35	5.6/5.3
u17	13-15	2.2-2.6	36/34	5.5/5.2
u18	12-14	2.0-2.4	35/35	5.3/5.3

Accuracy – error estimation

$$v_{||}^{*} = \beta c \frac{\Delta p}{p} = \frac{\beta c}{\eta_p} \frac{\Delta f}{f} = \frac{C}{\eta_p} \cdot \Delta f$$

	Value	Estimated Relative error	Comment
C	81.76 m	± 0.1 %	Exact orbit in unknown in arcs.
η_p	0.783	± 0.5 %	From optics
Δf	Varied around 1129.0 kHz	± 0.01 %	Determined by accuracy in frequency generator.
$v_{\|\|}$		± 0.5 %	Total estimated relative error.

C = Circumference; η_p = slip factor; f = rf frequency

Accuracy – error estimation

$$F_{\parallel} = \frac{Ze\hat{U}_{RF}\sin(\Delta\phi)}{L_C}$$

	Value	Estimated Relative error	Comment
U_{RF}	10.2	± 7 %	From synchrotron frequency measurements; η is known by ± 0.5 %
Δϕ	1° / 25.0 mV @ 50 Ω	± 1 %	Read as a voltage from phase discriminator. From input of a known phase difference to the phase discriminator
L_C	2.50 m	± 10 %	Effective cooler length. Affected by the toroidal field
$F_{\parallel}$		± 12 %	Total estimated relative error

Summary

• Longitudinal cooling force measurements in CELSIUS have been performed while varying different parameters such as magnetic field, electron current and alignment angle.

• Transient cooling longitudinally and transverse

• The data will be used in benchmarking of cooling force (See talk by A. Fedotov)