Emittance Growth and Beam Losses in the LANSCE Linear Accelerator

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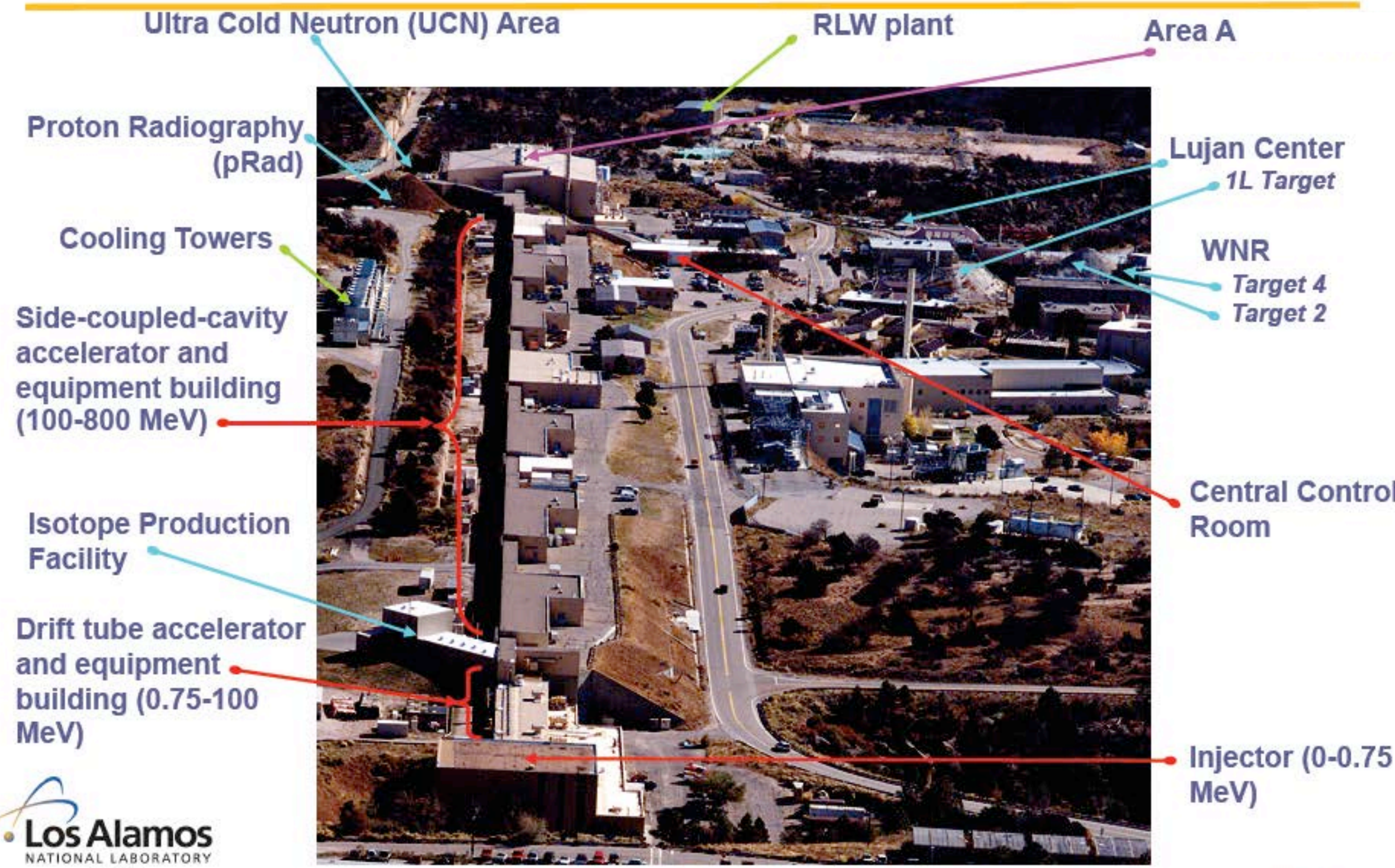
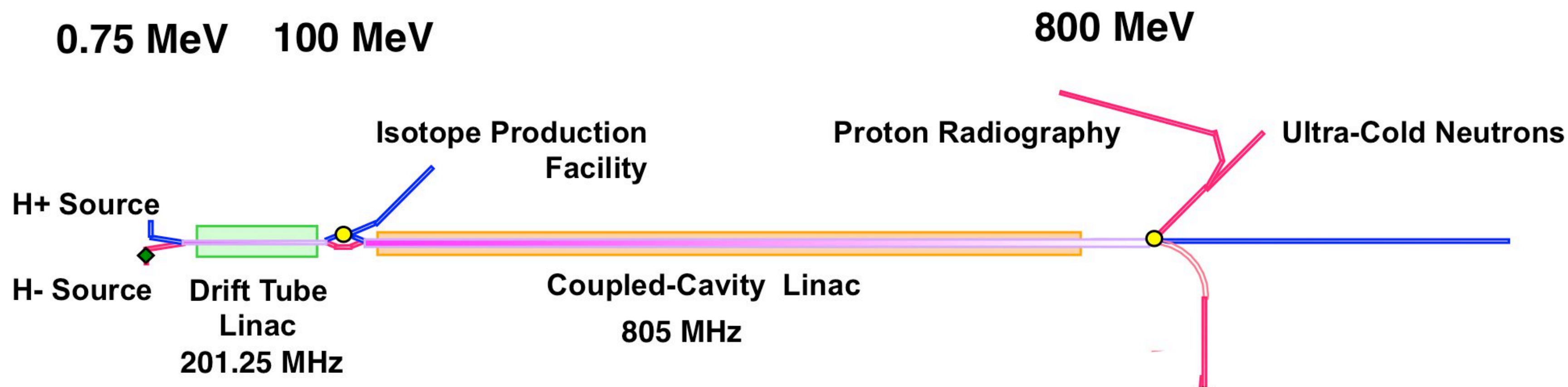
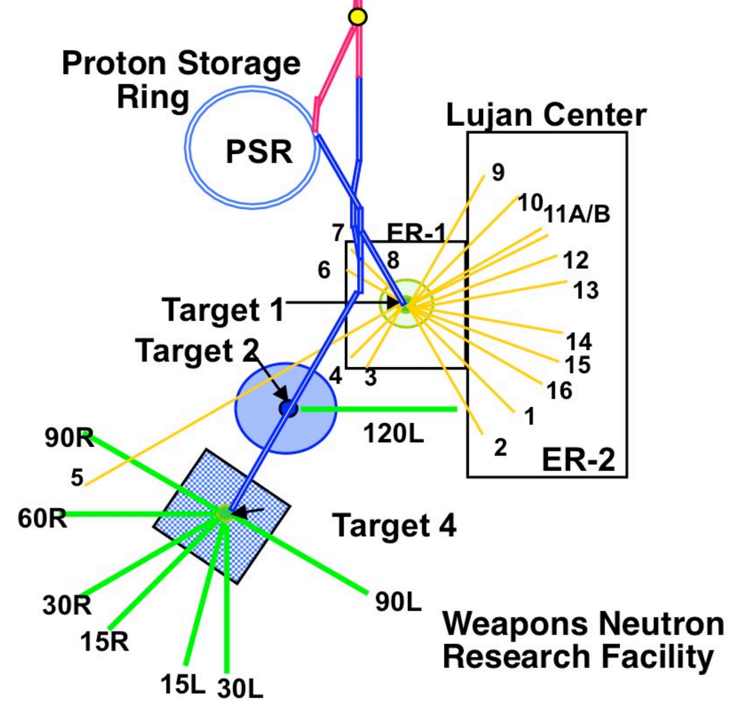
The LANSCE accelerator provides unique flexible time-structured beams from 100 to 800 MeV



LANSCE Facility Overview





Beam parameters at 120 Hz pulse rate (number in brackets are given for previous 60 Hz operation)

Area	Rep. Rate (Hz)	Pulse Length (µs)	Current / bunch (mA)	Average current (µA)	Average power (kW)
Lujan Center	20 (20)	625	10	100	80
Isotope Production	100 (40)	625	4 (10)	230	23
Weapons Neutron	100 (40)	625	25 (25)	4.5 (1.8)	3.6 (1.4)
Proton Radiography	1	625	10	< 1	< 1
Ultra-Cold Neutrons	20 (20)	625	10	10	8

Beam Loss Measurements

Activation Protection (AP) devices are liquid scintillator and photomultiplier tube, which are used throughout the Linac, Switchyard, and Lines B/C/D/1R/1L

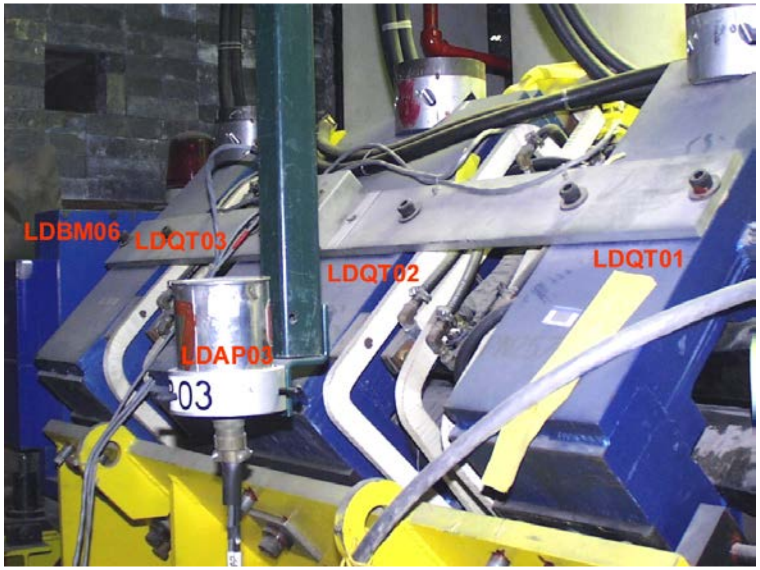
- AP are calibrated so that 100% integrated signal output is equivalent to 100 nA of beam loss
- A Loss Monitor (LM) is an AP can where the signal is not integrated and therefore we see a real-time of beam loss across the beam pulse

Ion Chamber (IR) detectors are used in the high energy transport lines (Line D, PSR, 1L, WNR)

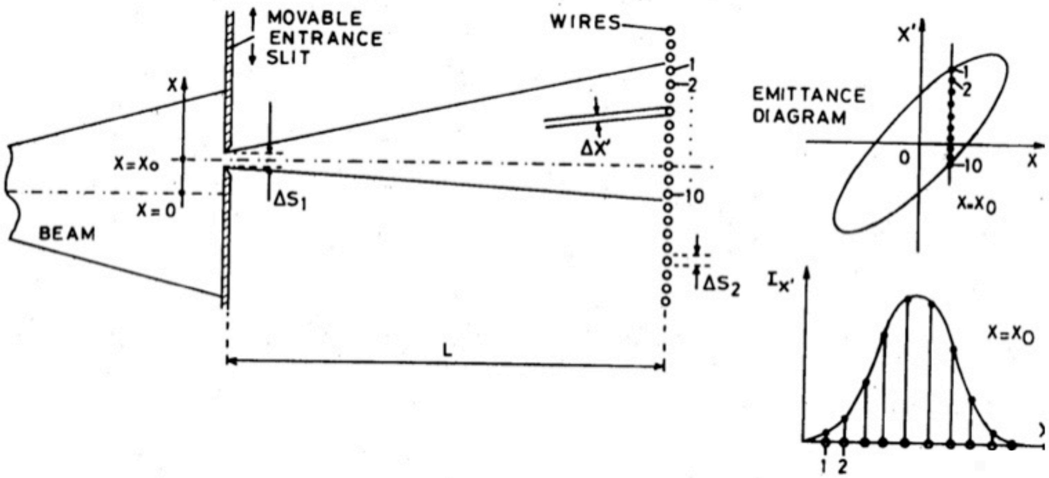
- Usually located in parallel with a GD that feeds into Radiation Safety System
- Ion chamber will not saturate at high loss rates like AP cans

Hardware Transmission Monitors (HWTM)

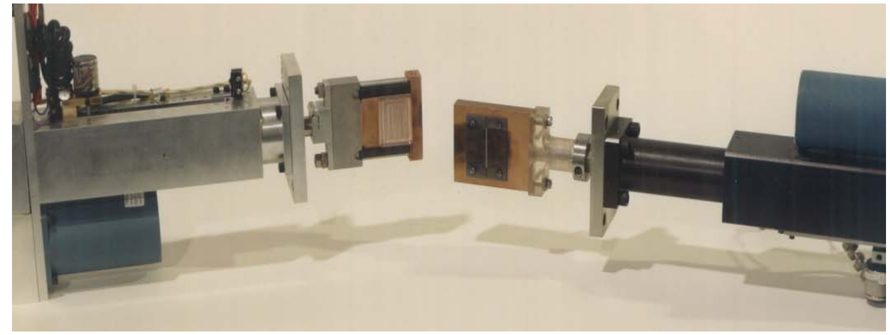
- The HWTM system measures and limits the beam current losses between current monitors



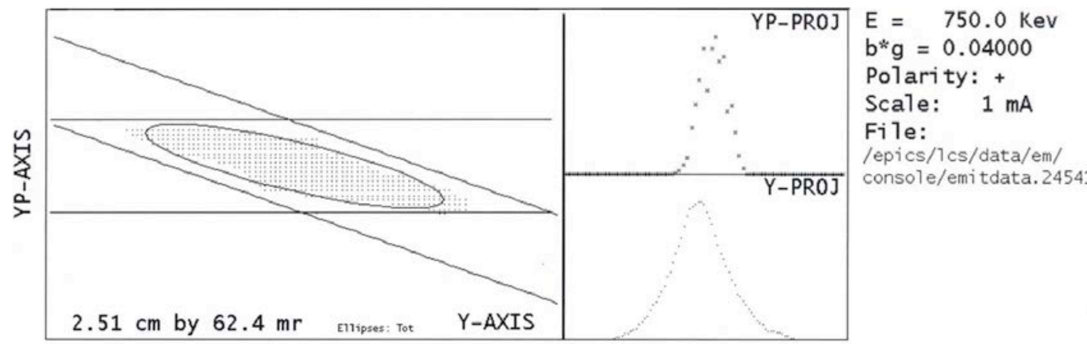
Slit-Collector Emittance Measurements (up to 100 MeV)



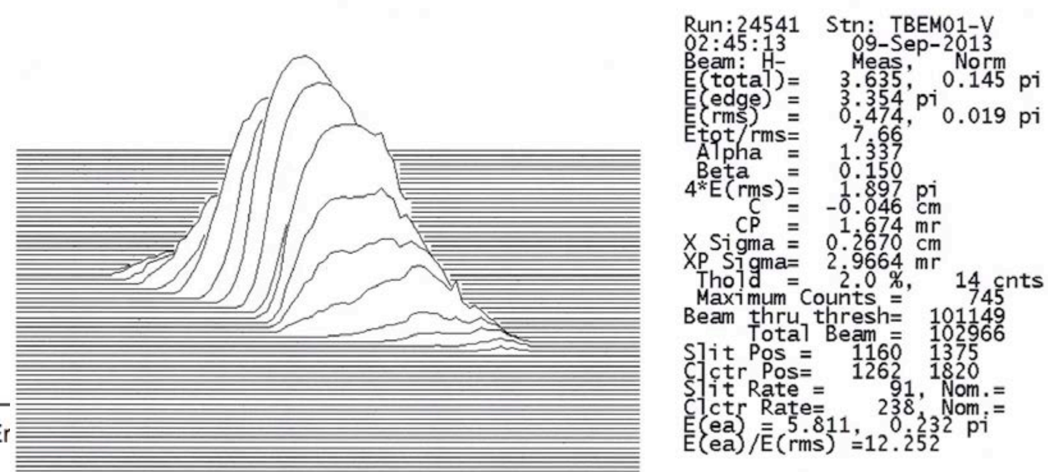
Emittance measuring device.



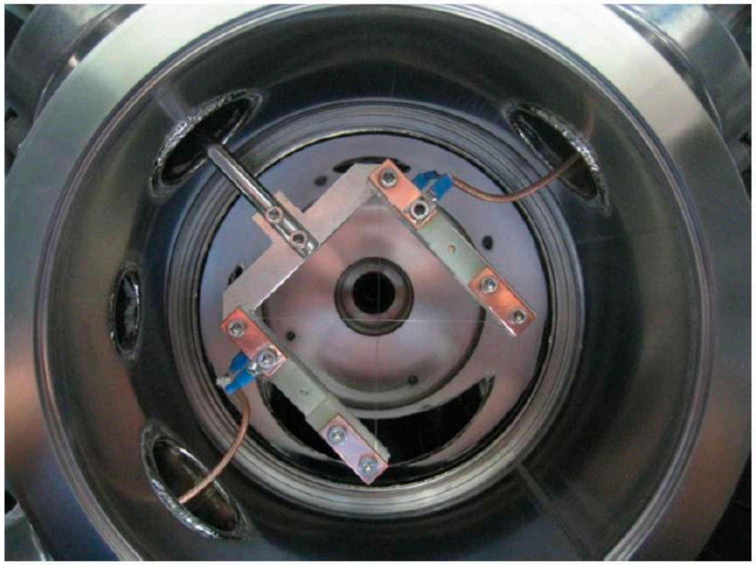
Slit and Collector Actuators

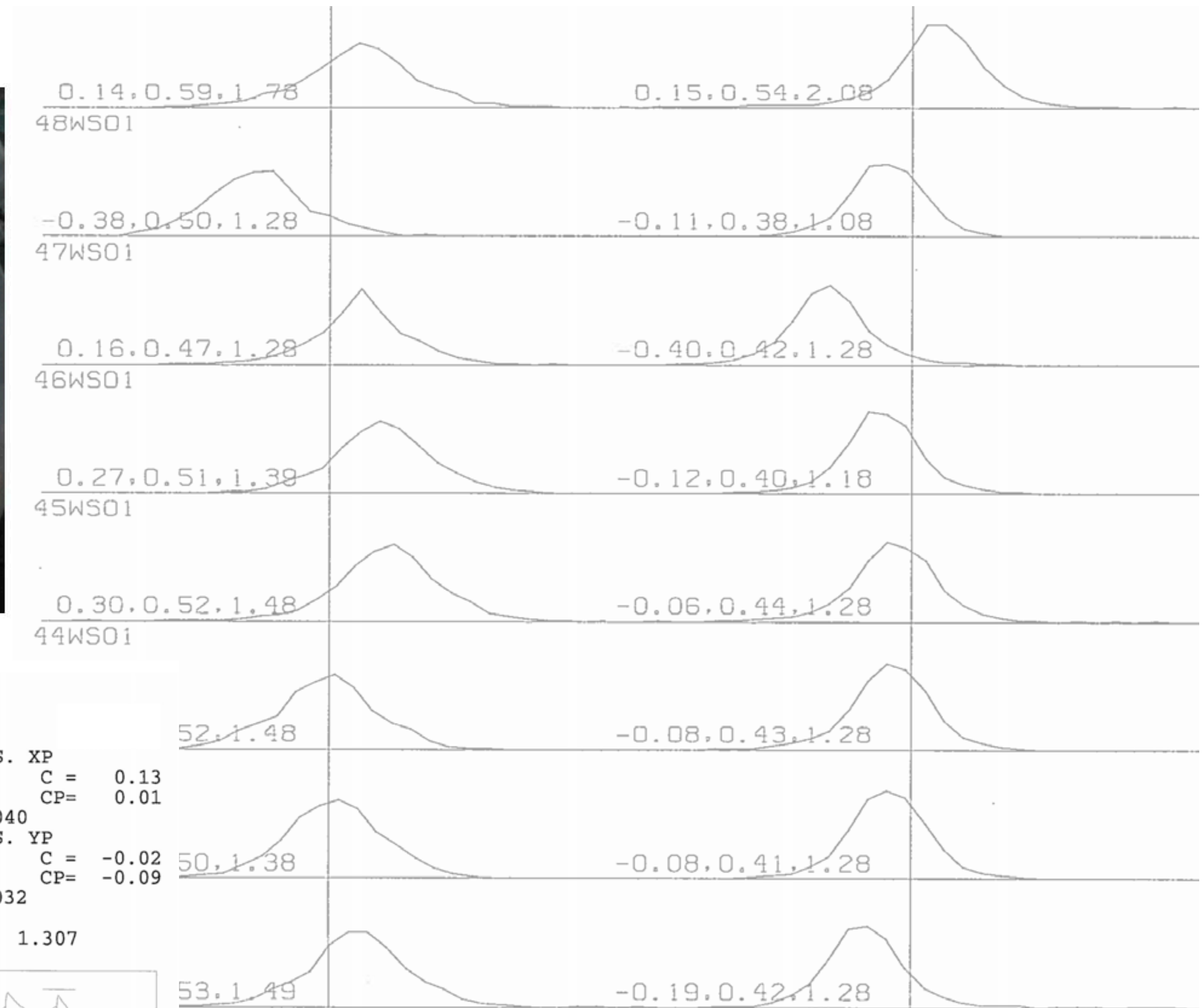


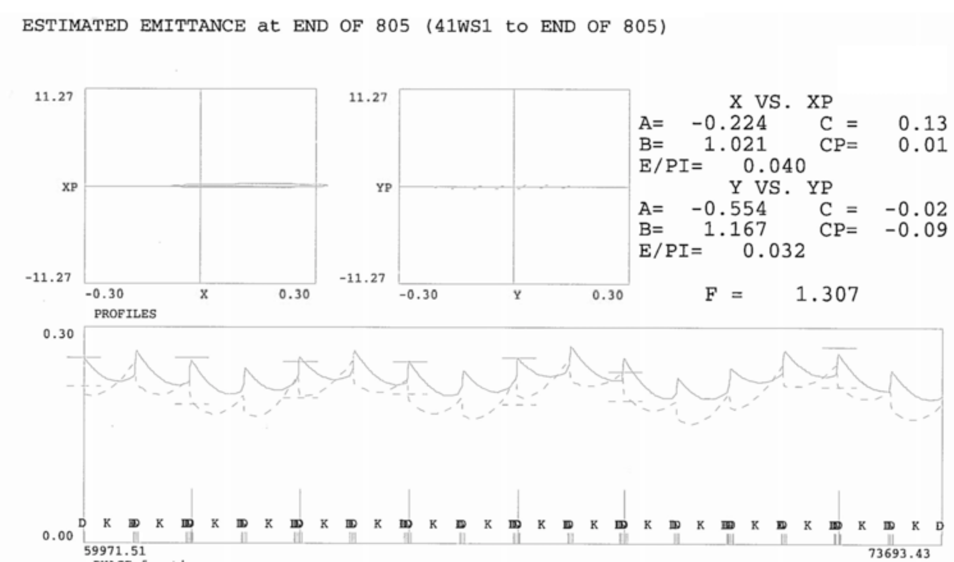
Threshold of 2% out of peak value of beam distribution is added to remove experimental noise



Wire Scans for Emittance Measurements (> 100 MeV)





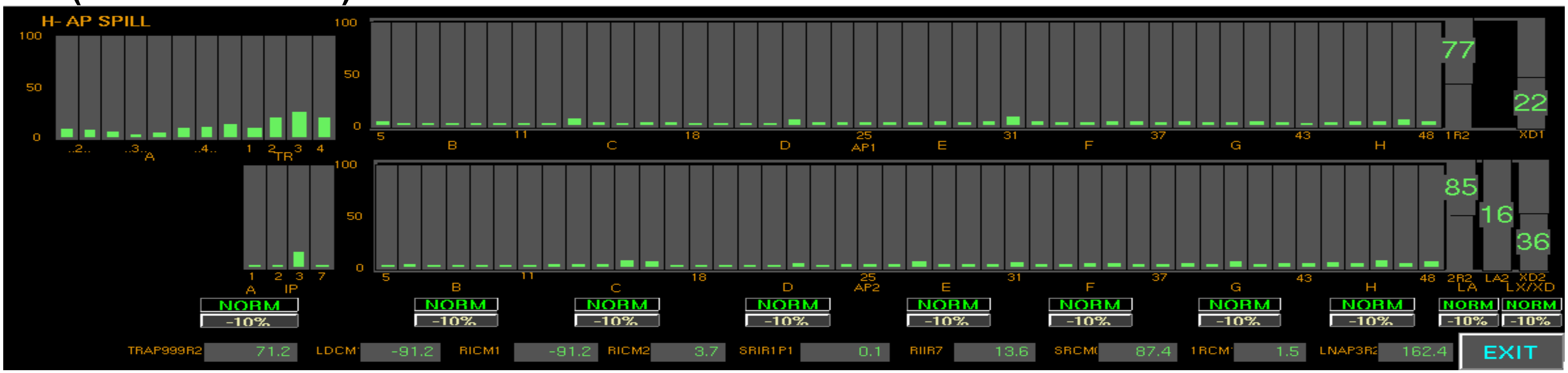


Beam Losses in the Linear Accelerator

Drift Tube Linac (0.75 – 100 MeV)

Transition Region

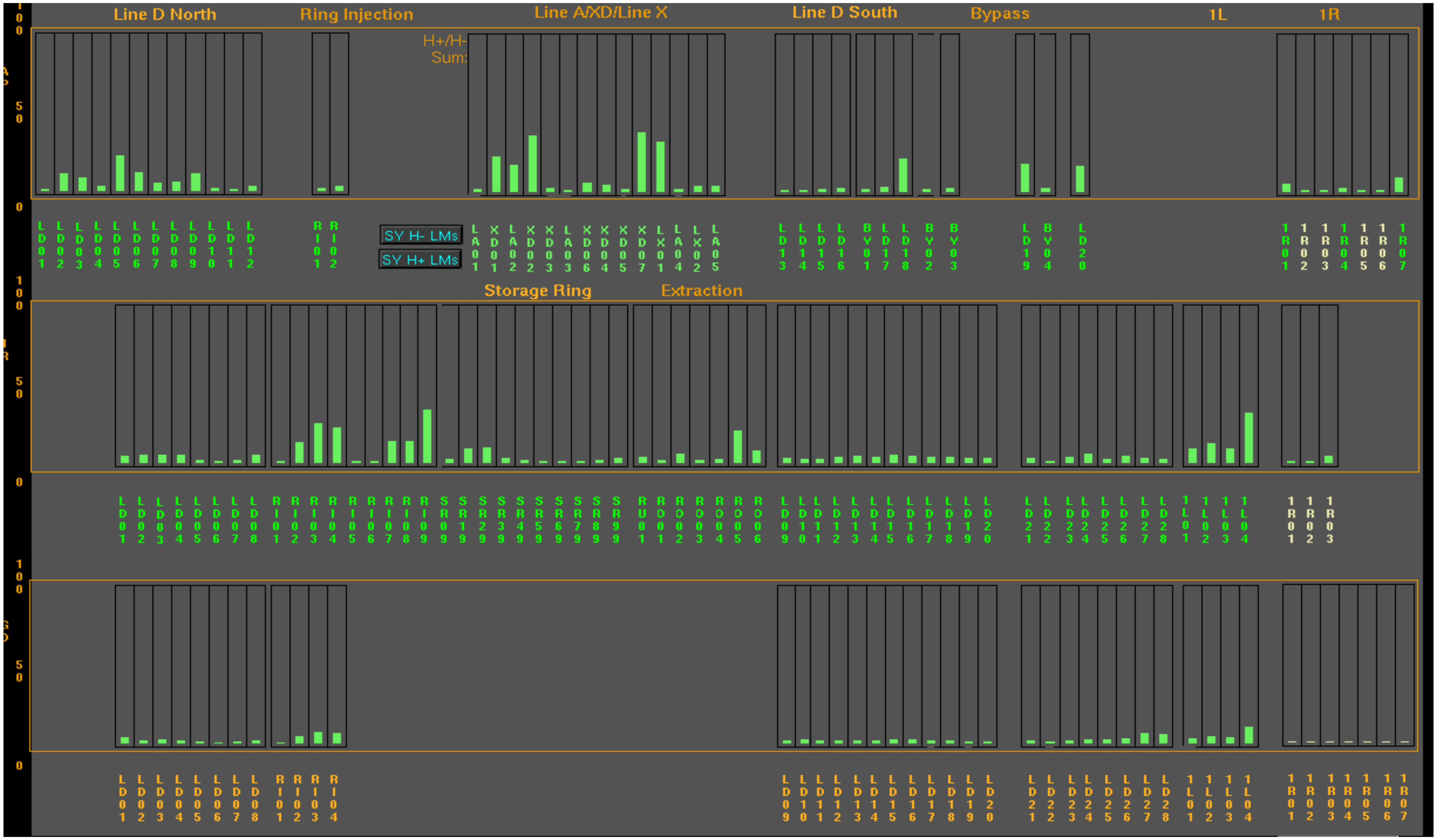
Coupled- Cavity Linac (100 MeV – 800 MeV)



Average beam loss in linac:
$2 \times 10^{-3} \sim 3 \times 10^{-6}\ m^{-1} \sim$ 0.2 W/m.

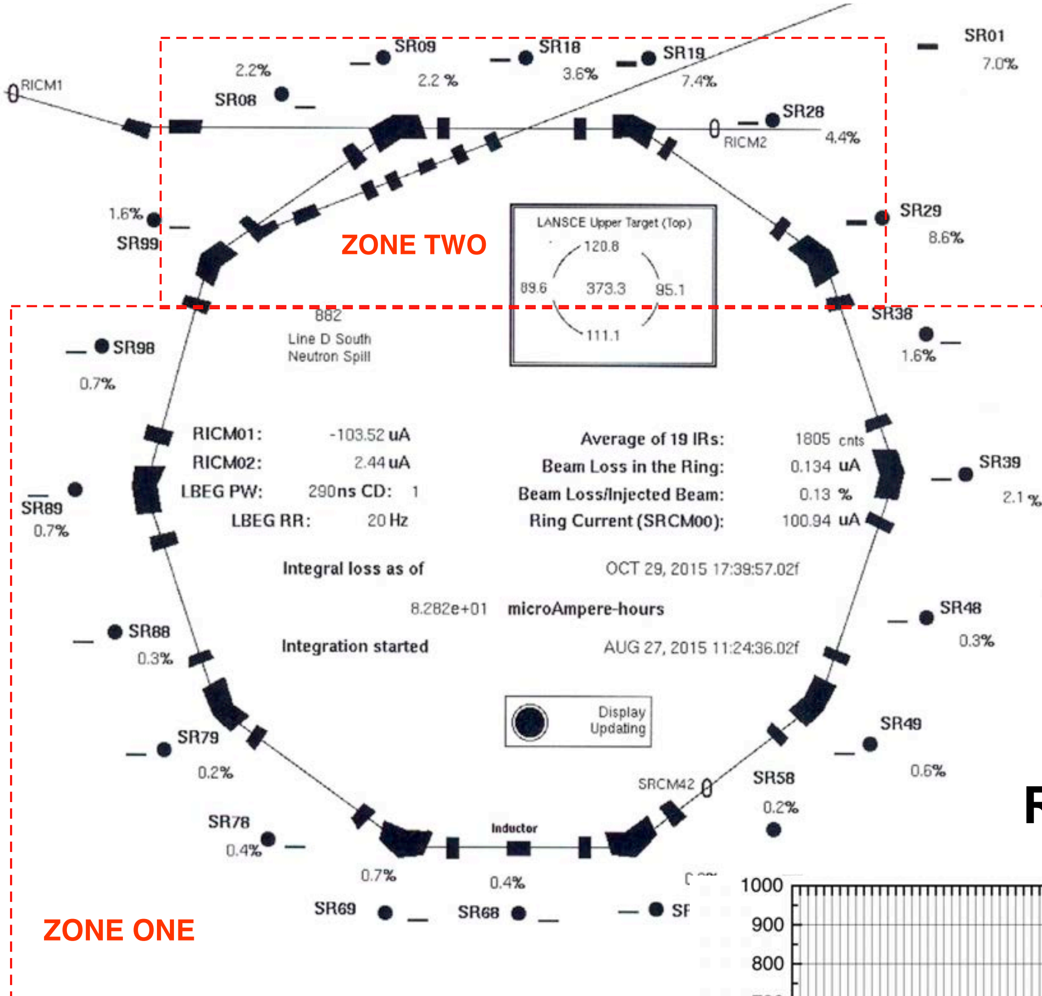
Year	Pulse Rate (Hz)	Summed Loss Monitor Reading (A.U.)
2017	120	150
2016	120	190
2015	120	135
2014	60	211
2013	60	190

Beam Losses in the 800 MeV High-Energy Beam Transport



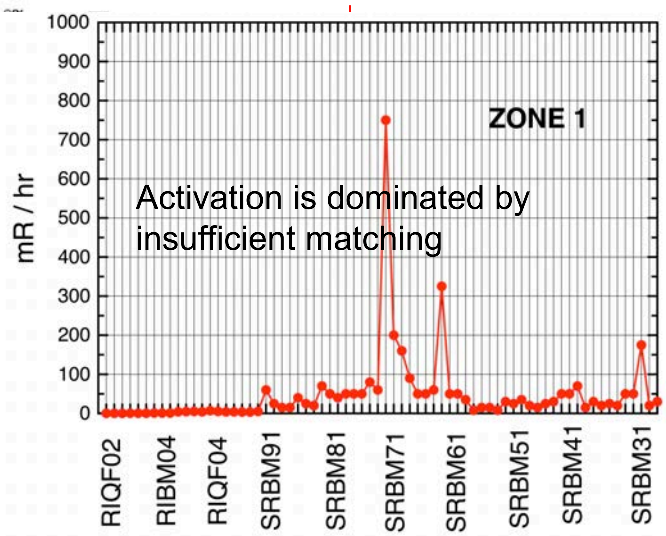
Average beam loss in high - energy beamlines ~ $4x10^{-3}$ ~ $2x10^{-5}$ m^{-1} ~ 1.6 W/m

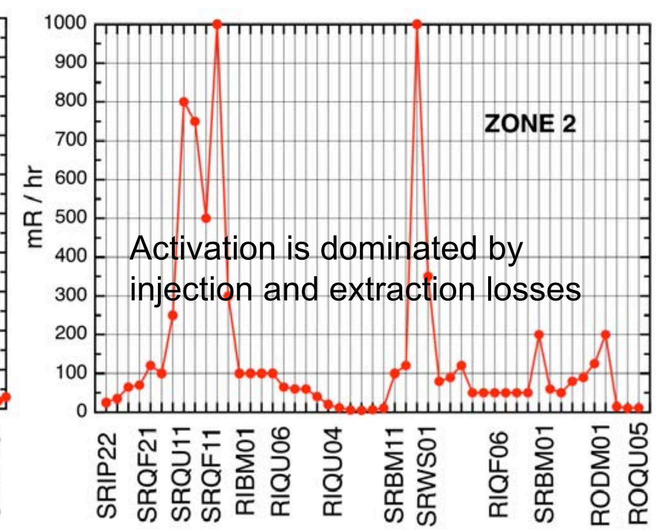
Beam Losses in Proton Storage Ring (PSR)



Year	PSR Pulse Rate (Hz)	PSR Beam Losses (%)
2017	20	0.32
2016	20	0.32
2015	20	0.13
2014	20	0.24
2013	20	0.24

Results of 2017 PSR radiation survey



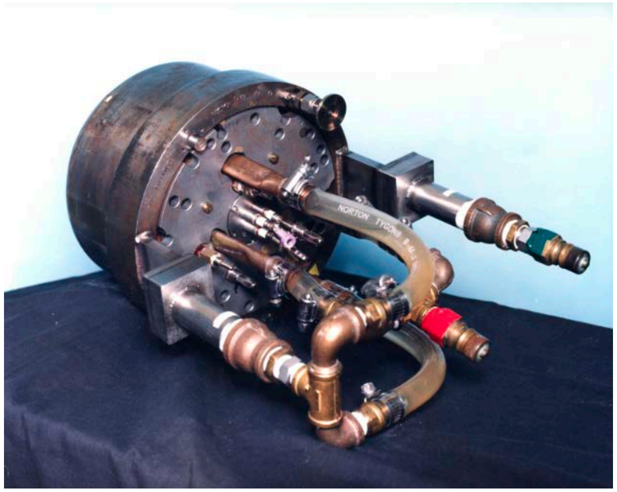


Main Sources of Emittance Growth and Beam Losses

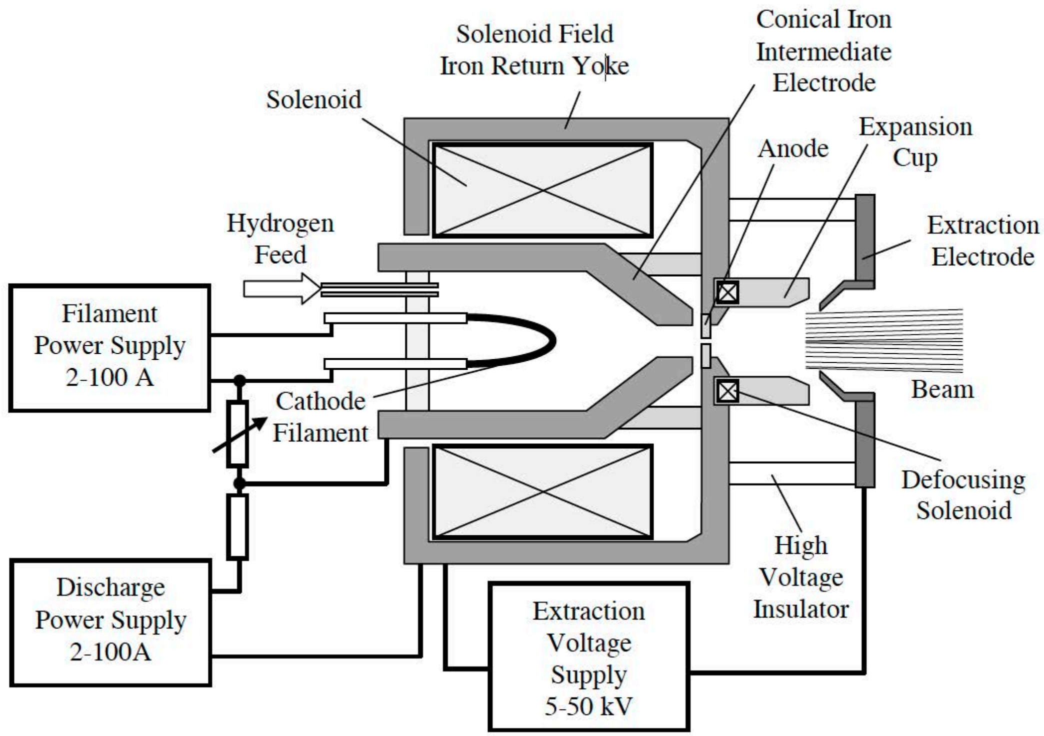
1. Misalignments of accelerator channel components
2. Transverse-longitudinal coupling in RF field
3. Particle scattering on residual gas, intra-beam stripping
4. Nonlinearities of focusing and accelerating elements
5. Non-linear space-charge forces of the beam

6. Mismatch of the beam with accelerator structure
7. Instabilities of accelerating and focusing field
8. Beam energy tails from un-captured particles
9. Dark currents from un-chopped beam
10. Excitation of higher-order RF modes

Duoplasmatron Proton Ion Source



Side view of assembled LANSCE duoplasmatron proton ion source.

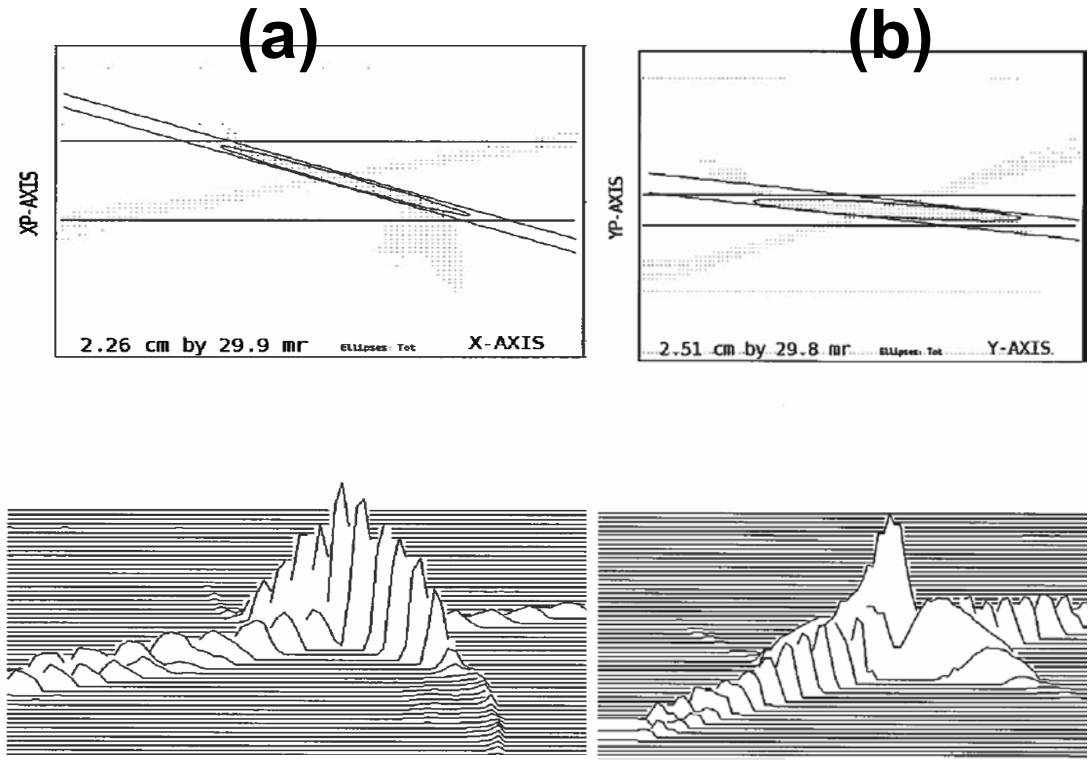


Normalized beam emittance due to thermal spread of particles in plasma:

$$\varepsilon_{rms} = \frac{R}{2}\sqrt{\frac{kT}{mc^2}}$$

Pulse Rate (Hz)	Pulse Length (μs)	Beam Current (mA)	Normalized rms emitttance (π cm mrad)
40	830	13	0.003-0.004
100	830	5	0.002-0.003

Increasing the Beam Brightness of Proton Ion Source

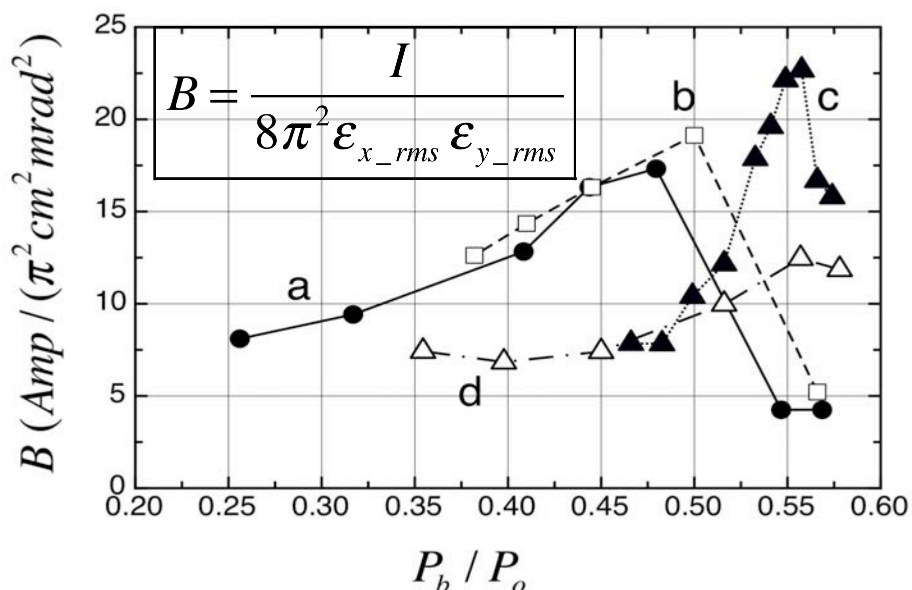


Emittance of the beam extracted from a proton ion source: (a) before and (b) after source adjustments. Beam distribution contains additional H_2^+ / H_3^+ components.

(Y.Batygin et al, Rev. Sci. Inst., 85, 103301, 2014)

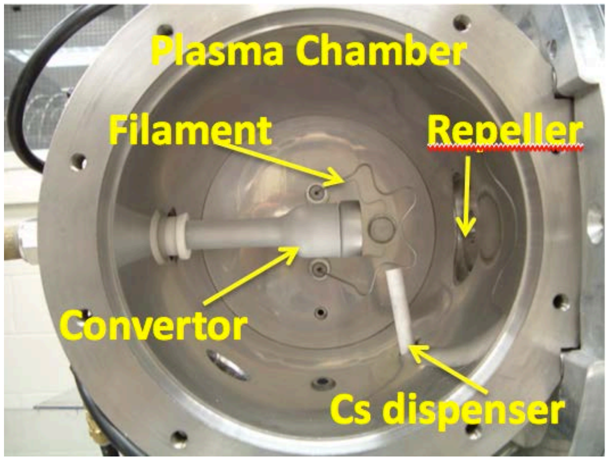
Matching parameter: ratio of beam perveance to Child-Langmuir perveance

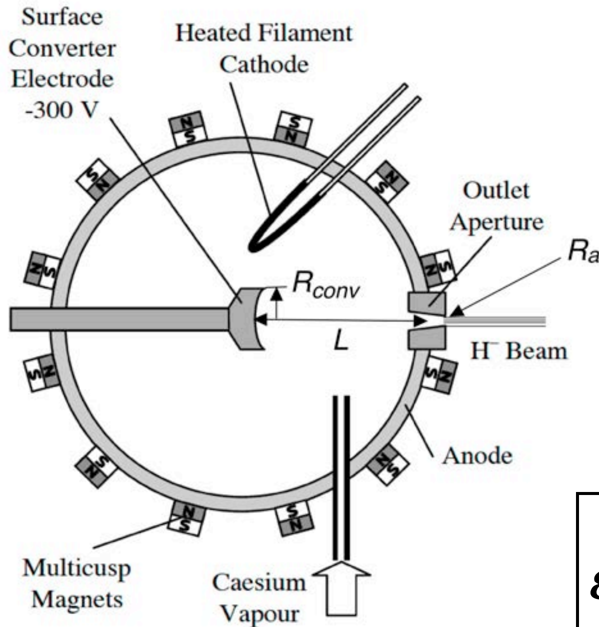
$$\eta = \frac{P_b}{P_o} = \frac{9}{\sqrt{2}S^2}\frac{I}{I_c}\left(\frac{mc^2}{qU_{ext}}\right)^{3/2}$$



Measured beam brightness as function of matching parameter peaking at optimal value η_{opt} = 0.52.

H^- Ion Source

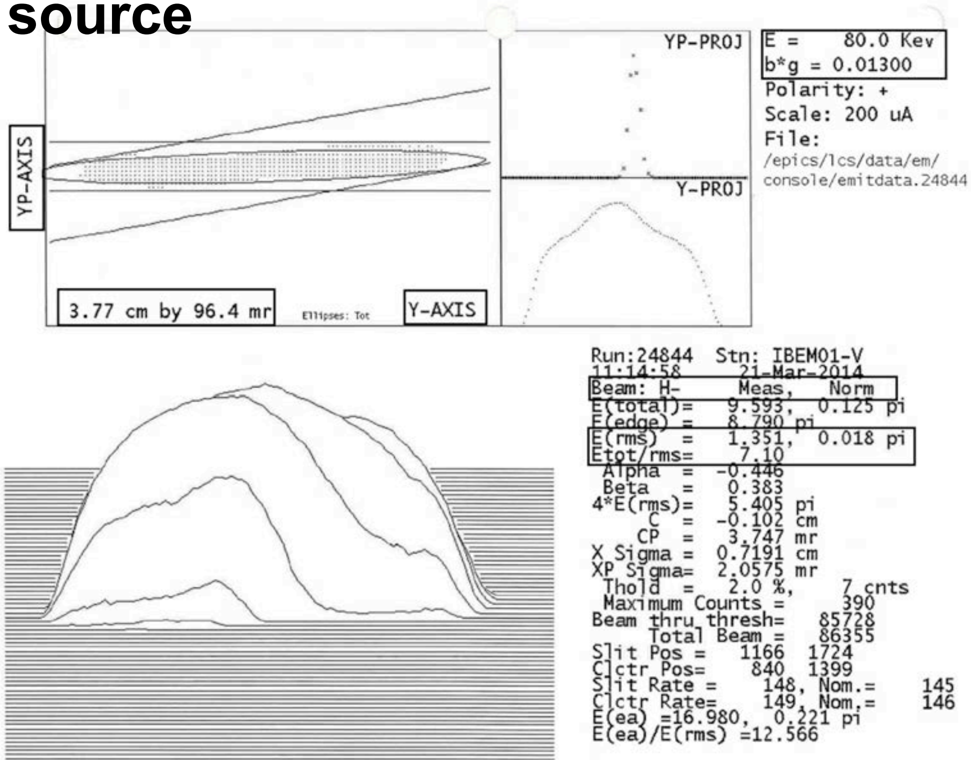




Normalized acceptance (admittance) of surface-production H^- ion source:

$$\varepsilon = \frac{4}{\pi}\sqrt{\frac{2eU_{conv}}{mc^2}\frac{R_{conv}R_a}{L}}$$

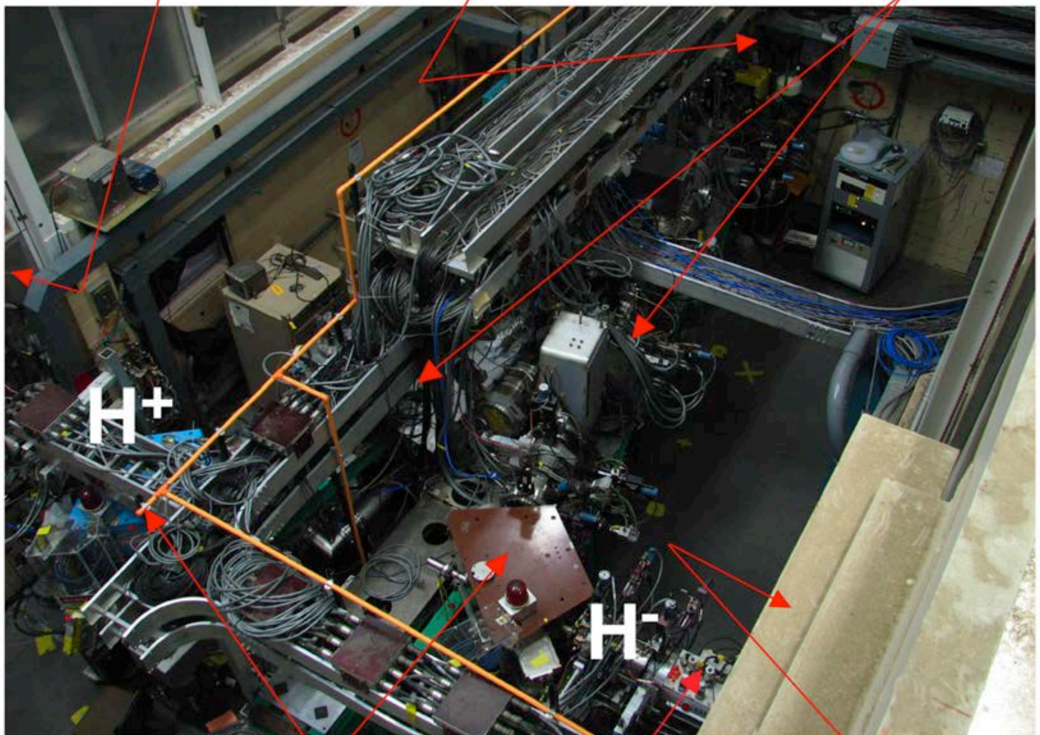
Cesiated, multicusp-field, surface-production H^- ion source



H^- beam emittance (π cm mrad) as a function of converter voltage U_{conv}

U_{conv} (V)	Analytical estimation	Experimental $4\varepsilon_{rms}$ emittance
300	0.076	0.072
177	0.058	0.060

750 keV H$^+$/H$^-$ Low Energy Beam Transports



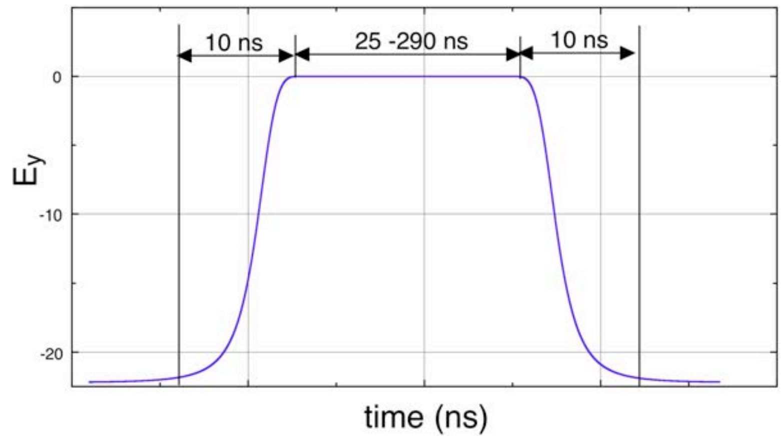
	H$^+$ Transport	H$^-$ Transport	Common H$^+$ / H$^-$ Transport
Length, m	10.2	9.8	2.5
Number of Quadrupoles	18	18	4
Vacuum, Torr	10^{-6}	10^{-6}	10^{-6}
Space Charge Neutralization, %	< 20	50 - 100	0 - 50
Peak Current , mA	5	15	4.5/14.5
Beam Loss, mA	0.4	0.4	0.1

Beam Emittance Growth in Low Energy Beam Transport

RF Bunching

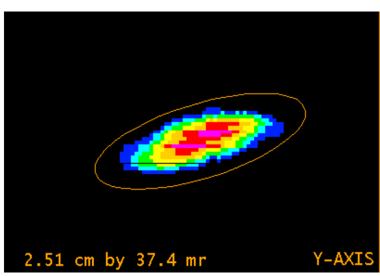
Beam	Emittance Growth $\varepsilon_{RF}/\varepsilon$
H^-	1.1 – 1.2
H^+	1.9 – 2.2

H^- Beam Chopping

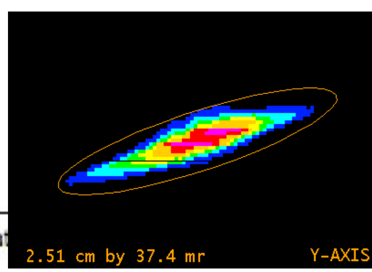


H^- Chopper Pulse	Emittance Growth $\varepsilon_{Ch}/\varepsilon$
290 ns	1.1
36 ns	1.3

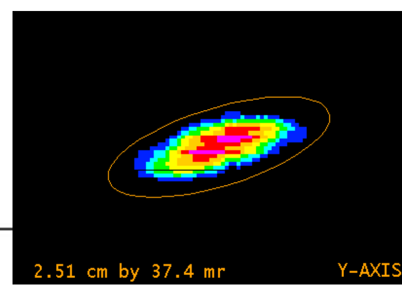
Bunchers Off



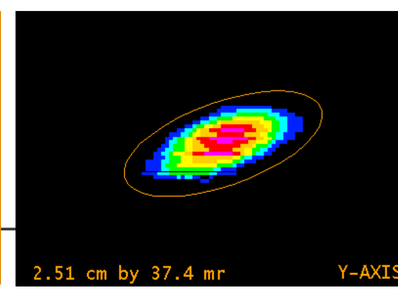
Bunchers On



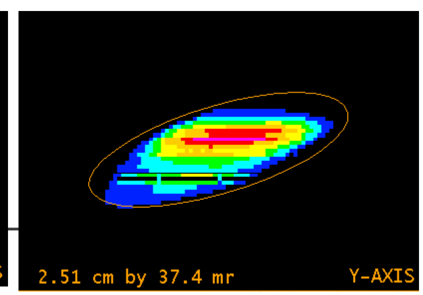
Chopper Off



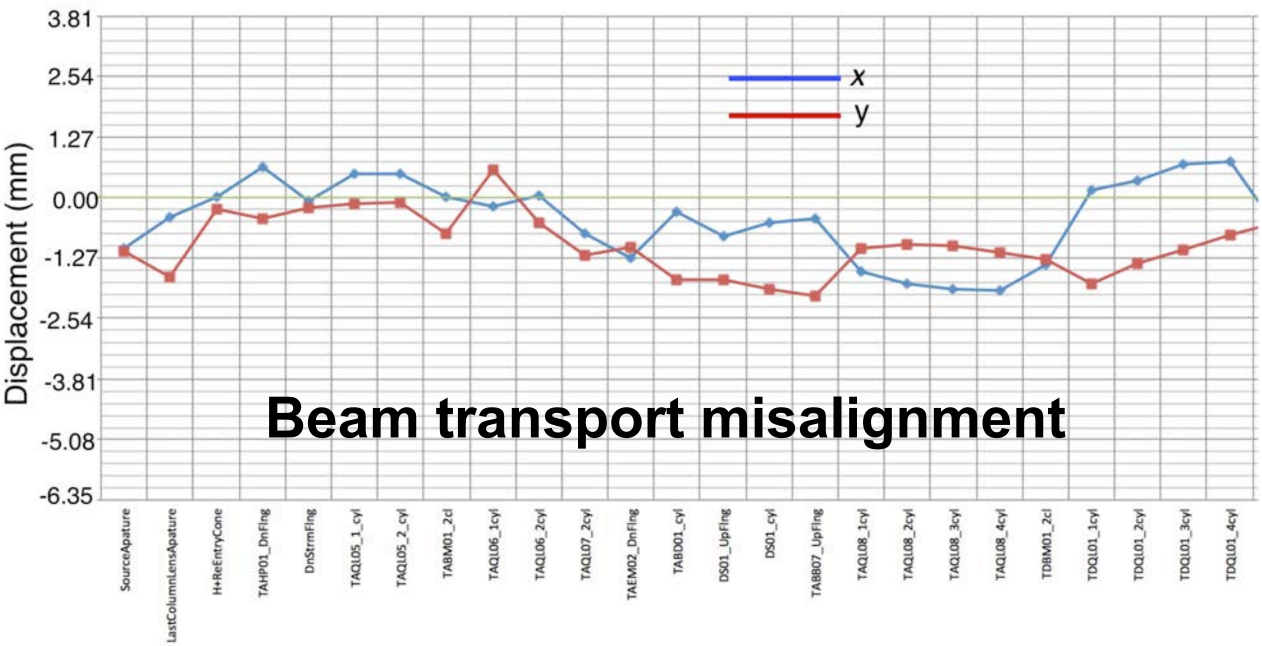
Chopper pulse 290 ns

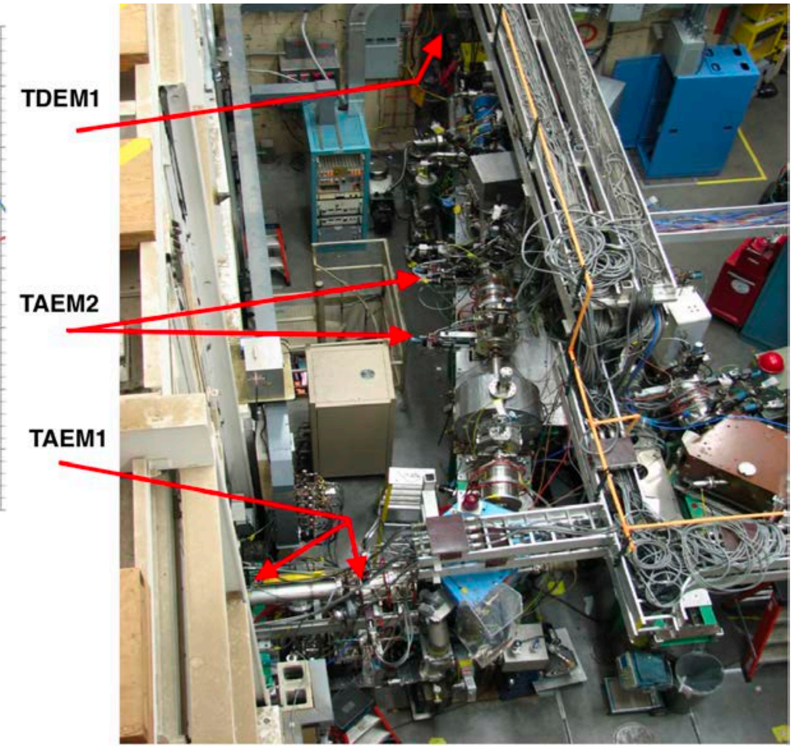


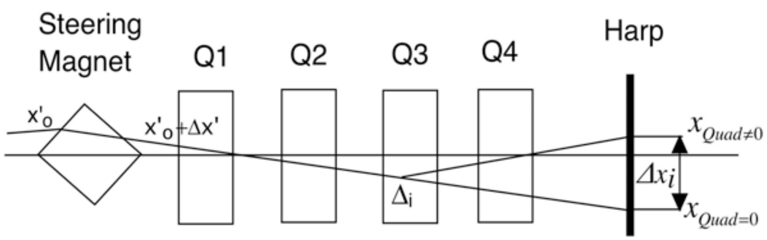
Chopper pulse 36 ns



Reduction of Proton Beam Emittance Growth in Low Energy Beam Transport





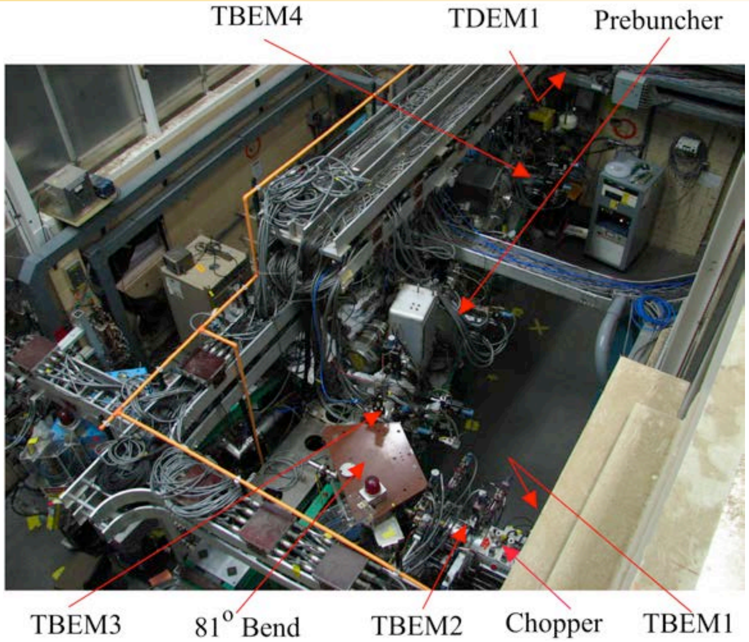


Minimization of beam offset in a sequence of quadrupoles

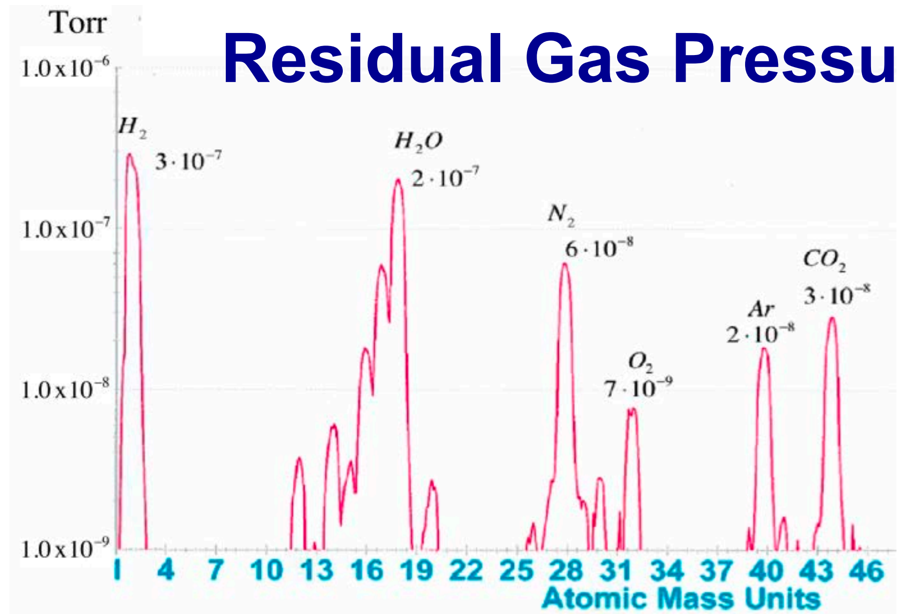
Emittance Station	Beam Emittance Before Alignment: Horizont/Vertical (π cm mrad)	Beam Emittance After Alignment: Horizont/Vertical (π cm mrad)
TAEM1	0.002 / 0.002	0.003 / 0.002
TAEM2	0.005 / 0.005	0.002 / 0.002
TDEM1	0.004 / 0.007	0.003 / 0.004

(Y.Batygin, IPAC17, TUPVA144)

Space Charge Neutralization of H⁻ Beam in the LEBT

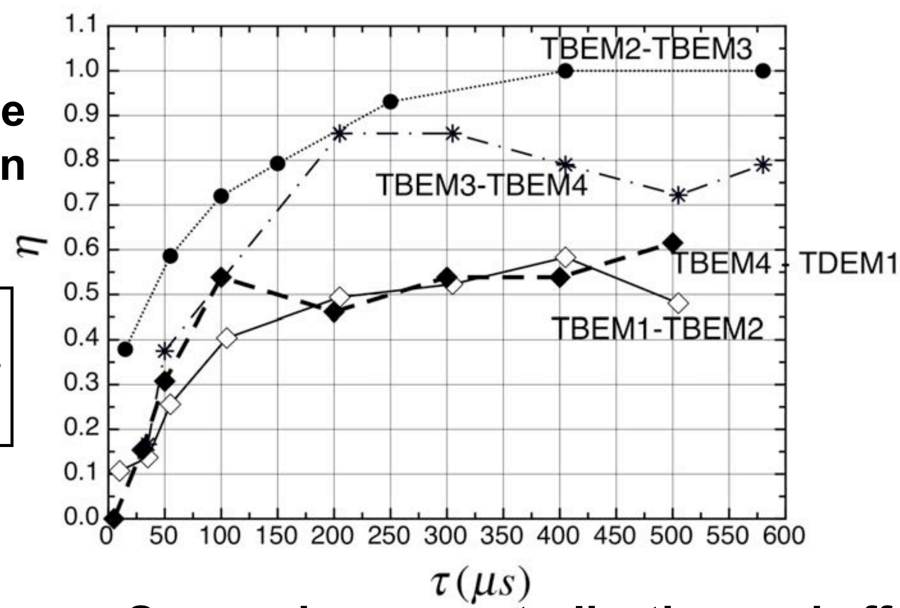


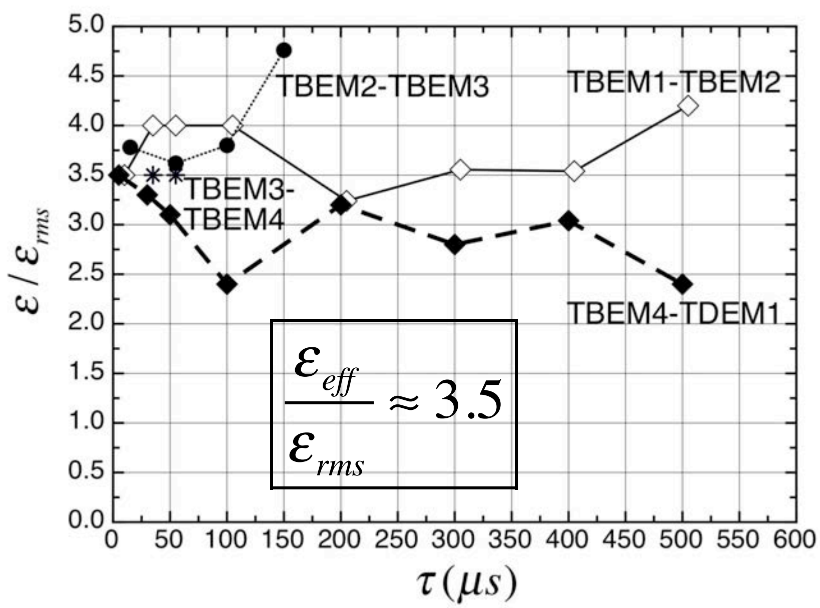
Residual Gas Pressure



Space charge neutralization factor:

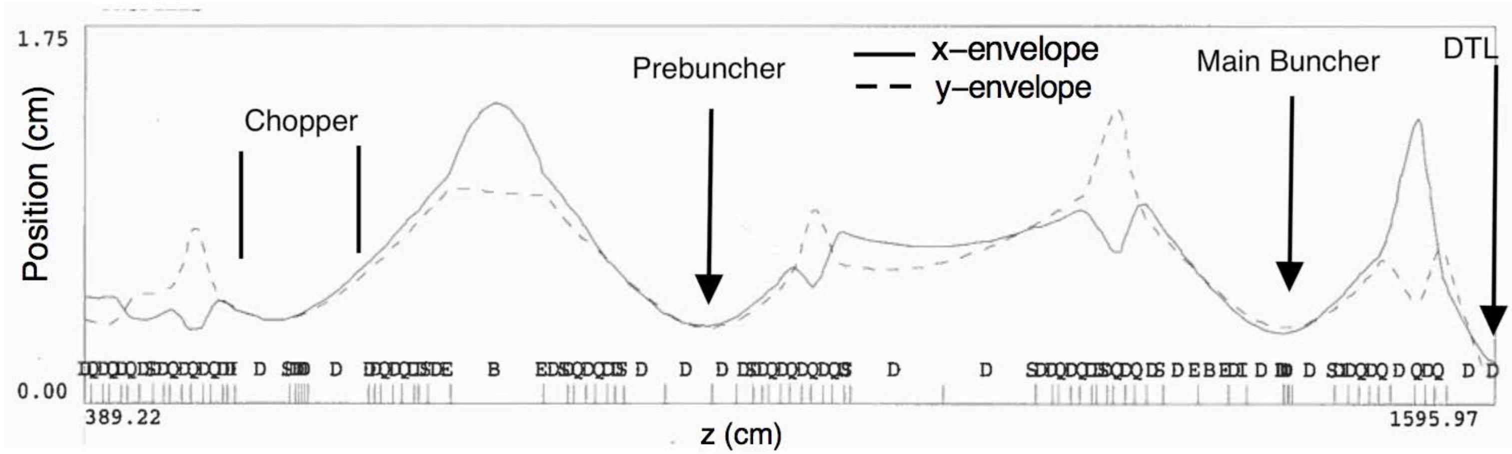
$$\eta = 1 - \frac{I_{eff}}{I_{beam}}$$





Space charge neutralization and effective beam emittance as functions of pulse length along the channel.

Improving H⁻ Beam Transmission in the LEBT



TRACE calculations of matched beam envelopes along H^- Low Energy Beam Transport.

(a)

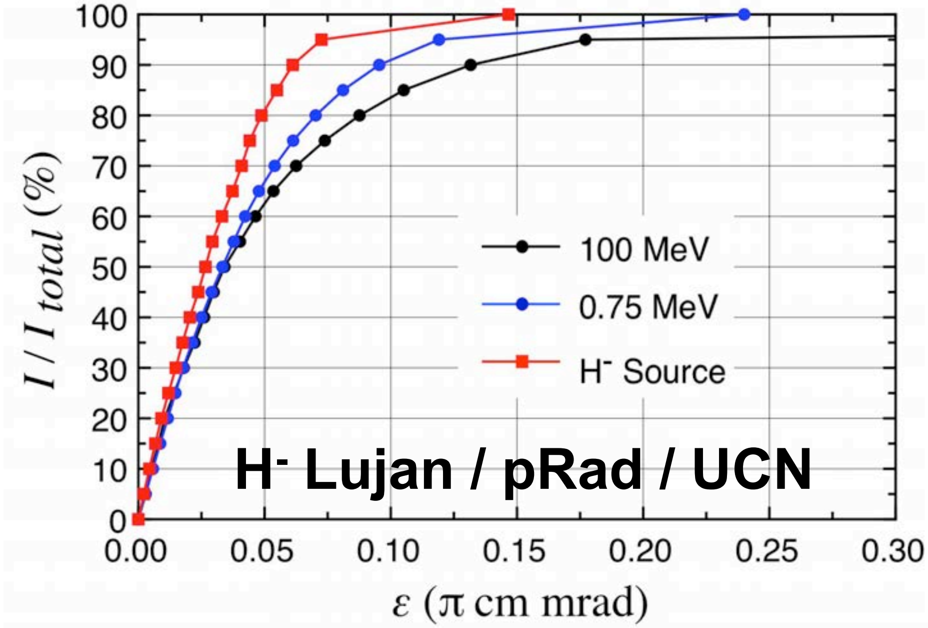
TBCM001I02	-15.7200 MA
TBCM002I02	-11.0000 MA
TBCM003I02	-10.2000 MA
TBCM004I02	-9.88000 MA
TBCM005I02	-9.80000 MA
TDCM001I02	-9.72000 MA

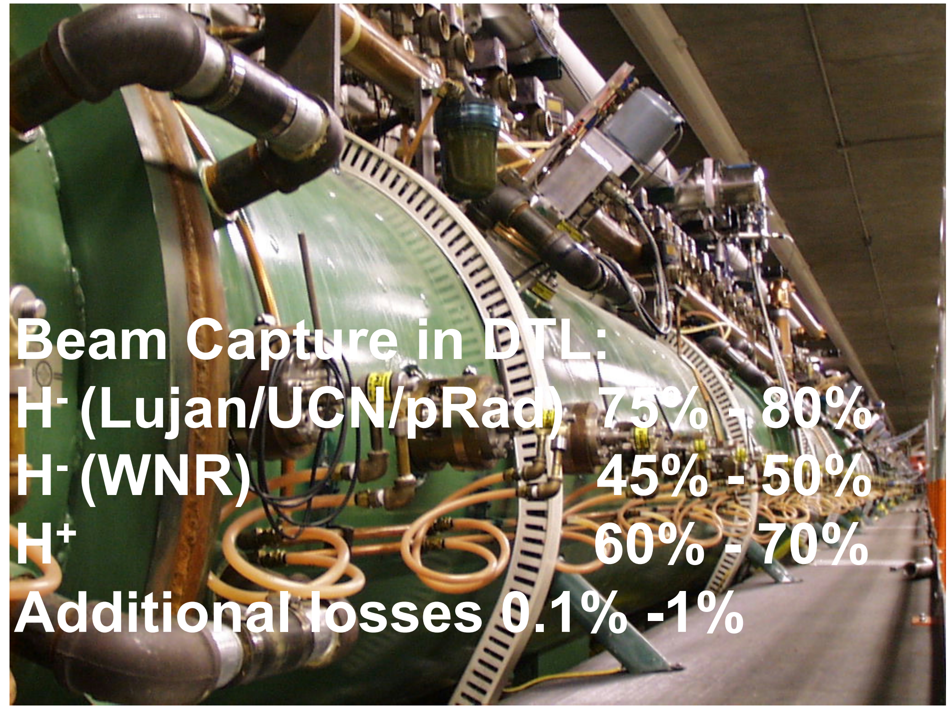
(b)

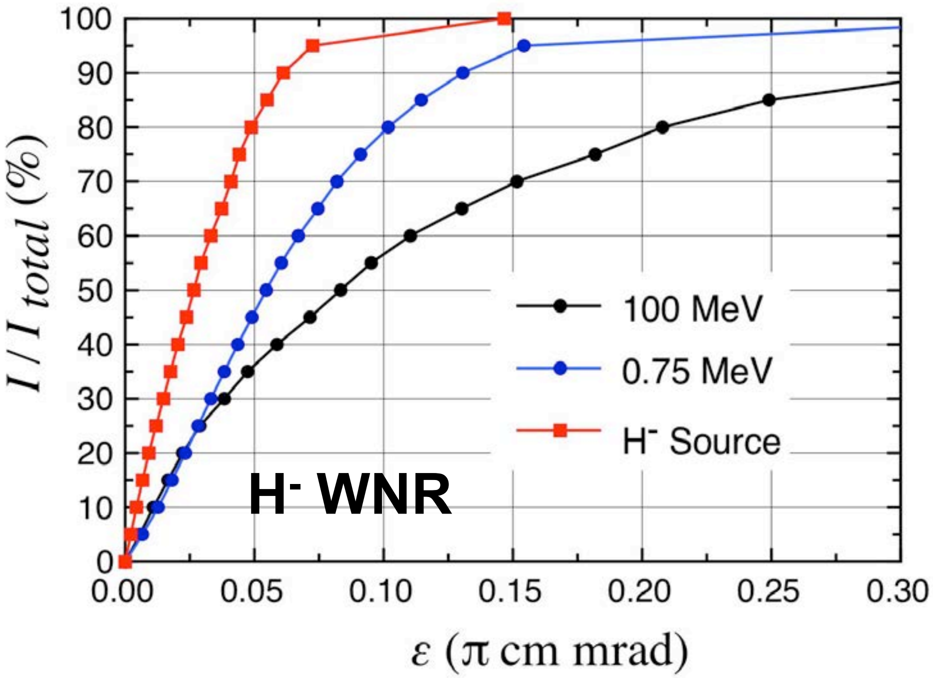
TBCM001I02	–13.8800 MA
TBCM002I02	–11.1000 MA
TBCM003I02	–10.6000 MA
TBCM004I02	–10.5200 MA
TBCM005I02	–10.4400 MA
TDCM001I02	–10.4200 MA

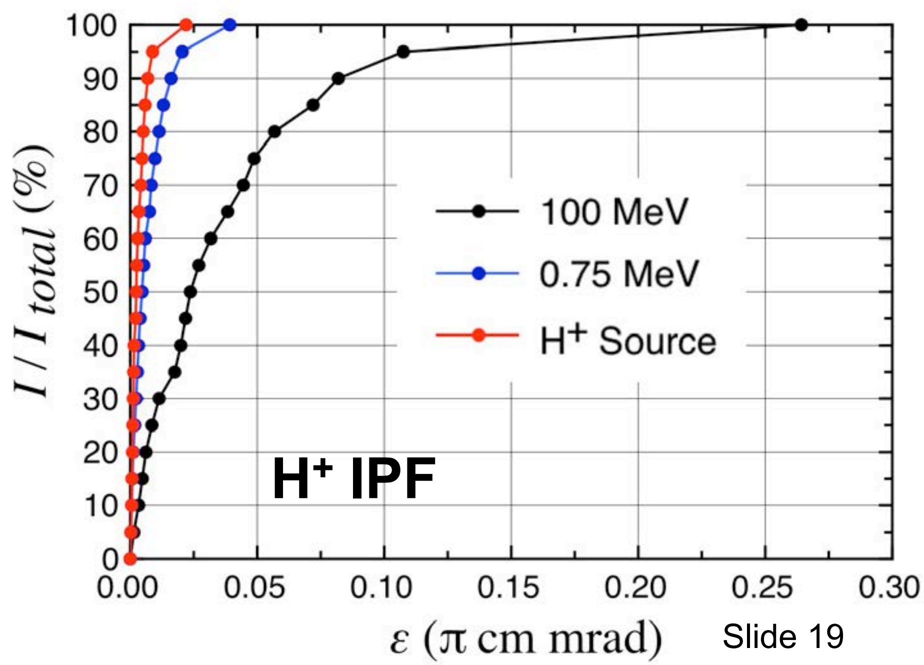
Transmission of tuned chopped H^- beam: (a) assuming full SC neutralization, (b) based on actual SC neutralization. Reduction of beam intensity (80%) between TBCM1 and TBCM2 is due to beam chopper.

Emittance Growth in DTL (0.75 MeV – 100 MeV)









Beam Emittance in LEBT and DTL (0.75 MeV – 100 MeV)

Normalized beam emittance (π cm mrad)

	H^- (Lujan / pRad /UCN)			H^- (WNR)			H^+ (IPF)		
	ε_{rms}	ε_{total}	$\boldsymbol{\varepsilon_{total} / \varepsilon_{rms}}$	ε_{rms}	ε_{total}	$\boldsymbol{\varepsilon_{total} / \varepsilon_{rms}}$	ε_{rms}	ε_{total}	$\boldsymbol{\varepsilon_{total} / \varepsilon_{rms}}$
Ion Source	0.018	0.11	**6.10**	0.018	0.11	**6.10**	0.002	0.01	**6.02**
0.75 MeV	0.022	0.14	**6.42**	0.034	0.219	**6.47**	0.004	0.027	**7.18**
100 MeV	0.041	0.34	**8.34**	0.058	0.415	**7.19**	0.02	0.17	**8.76**

Normalized beam emittance growth in DTL

H^- (Lujan / pRad /UCN)		H^- (WNR)		H^+ (IPF)	
$\frac{\varepsilon_{rms}(100)}{\varepsilon_{rms}(0.75)}$	$\frac{\varepsilon_{tot}(100)}{\varepsilon_{tot}(0.75)}$	$\frac{\varepsilon_{rms}(100)}{\varepsilon_{rms}(0.75)}$	$\frac{\varepsilon_{tot}(100)}{\varepsilon_{tot}(0.75)}$	$\frac{\varepsilon_{rms}(100)}{\varepsilon_{rms}(0.75)}$	$\frac{\varepsilon_{tot}(100)}{\varepsilon_{tot}(0.75)}$
1.86	2.42	1.7	1.89	5.0	6.3

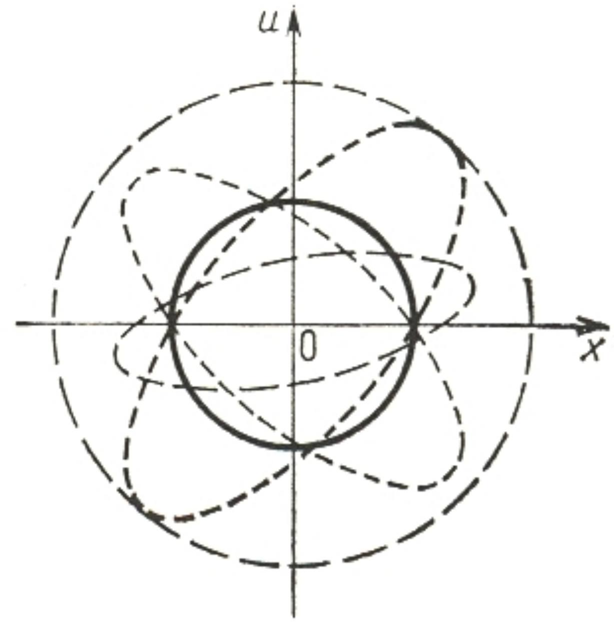
Beam Emittance Growth due to Transverse - Longitudinal Coupling in RF Field

$$\frac{\varepsilon}{\varepsilon_o} = 1 + \frac{\Phi}{\tan\varphi_s}\left(\frac{\Omega^2}{4\Omega_{rs}^2 - \Omega^2}\right)$$

Φ – phase length of the bunch,
ϕ_s – synchronous phase,
Ω – longitudinal oscillation frequency
Ω_{rs} – transverse oscillation frequency in presence of RF field.

In 201.25 MHz linac $\Phi \sim 1.57$ rad,
$\phi_s \sim 26^o$, $\Omega/\Omega_{rs} \sim 0.75$,
expected emittance growth:

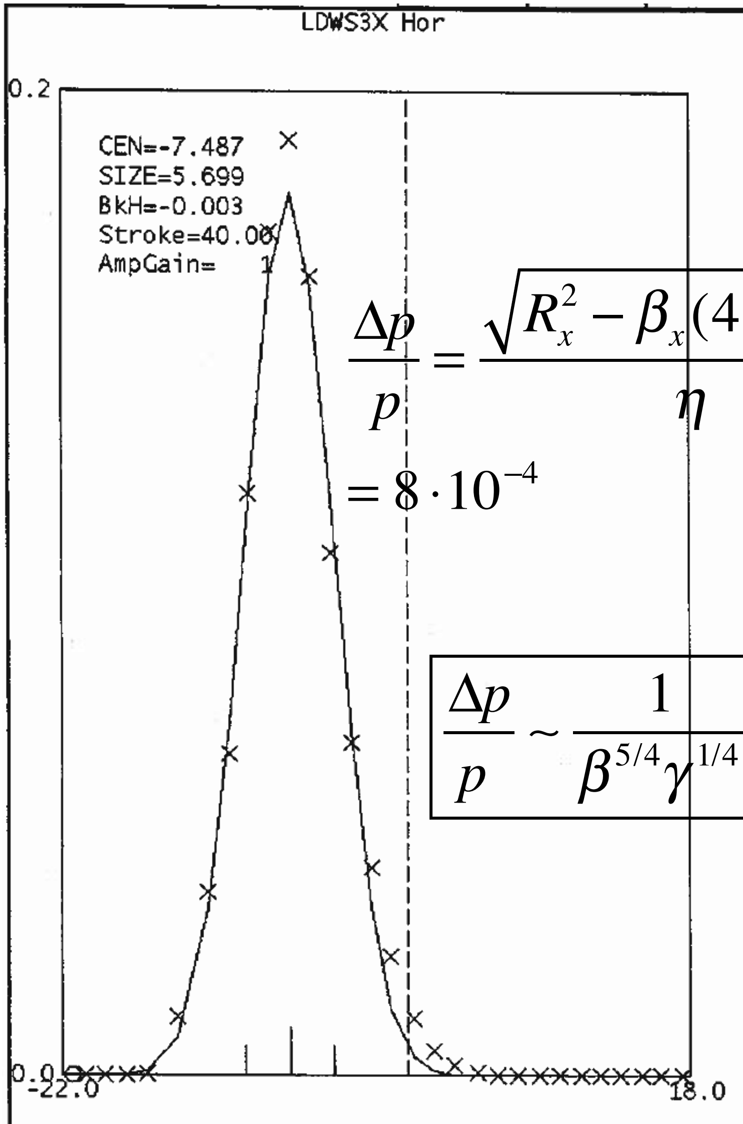
$$\varepsilon/\varepsilon_o = 1.62$$



Distortion of beam emittance in presence of RF field (I.M.Kapchinsky, "Theory of Linear Resonance Accelerators")

Longitudinal Beam Emittance

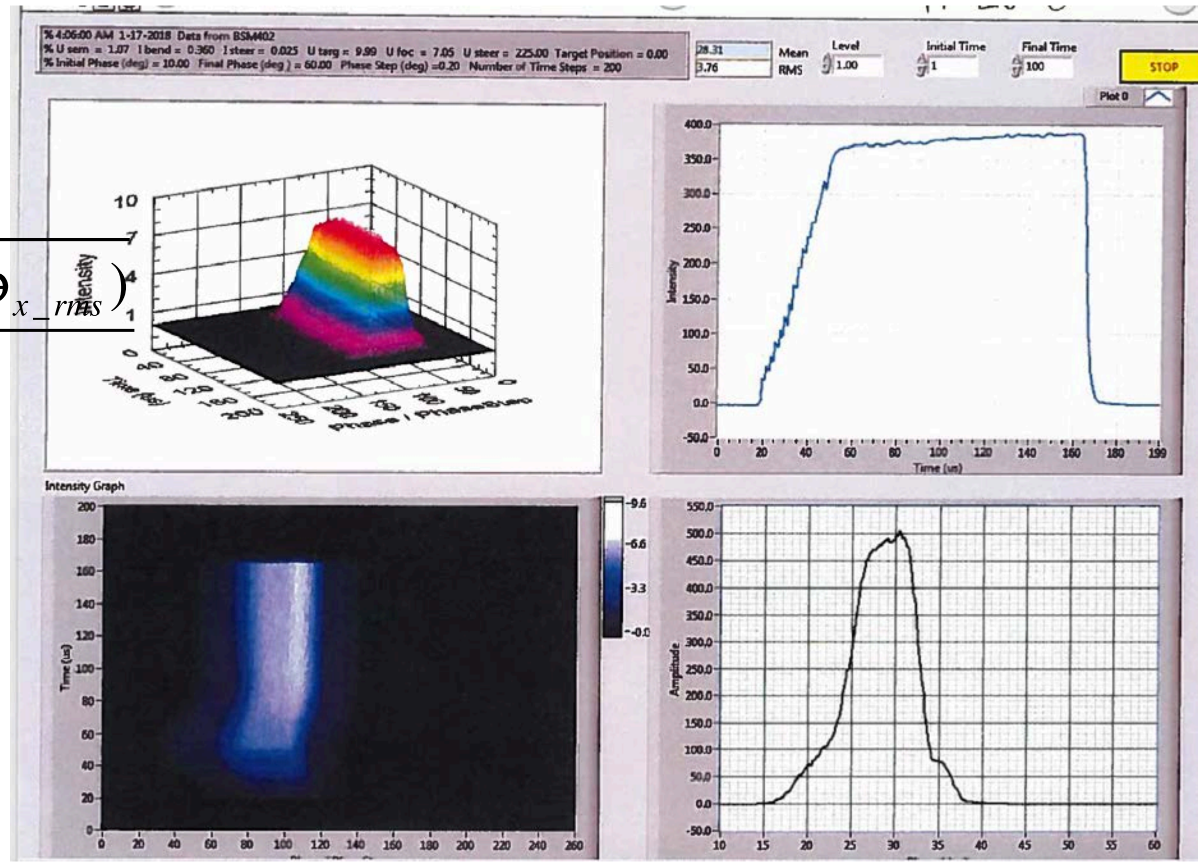
800 MeV Energy Spectrometer



$$\frac{\Delta p}{p} = \frac{\sqrt{R_x^2 - \beta_x (4\,\epsilon_{x\_rms})}}{\eta} = 8 \cdot 10^{-4}$$

$$\frac{\Delta p}{p} \sim \frac{1}{\beta^{5/4}\gamma^{1/4}}$$

Bunch shape monitor measurements at 70 MeV (I.Draganic et al, NAPAC16, MOA3CO03)

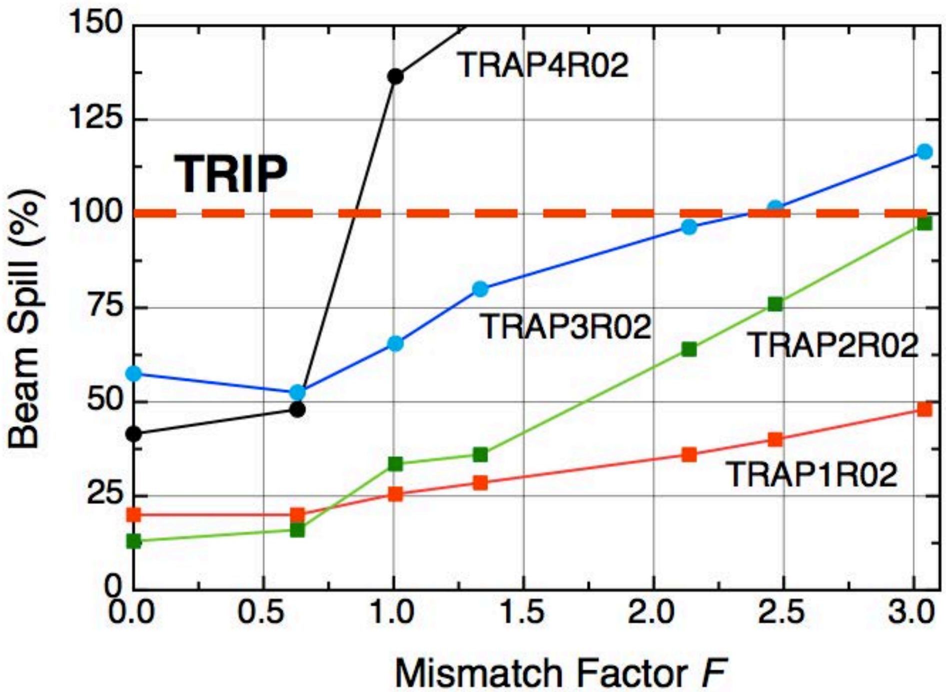


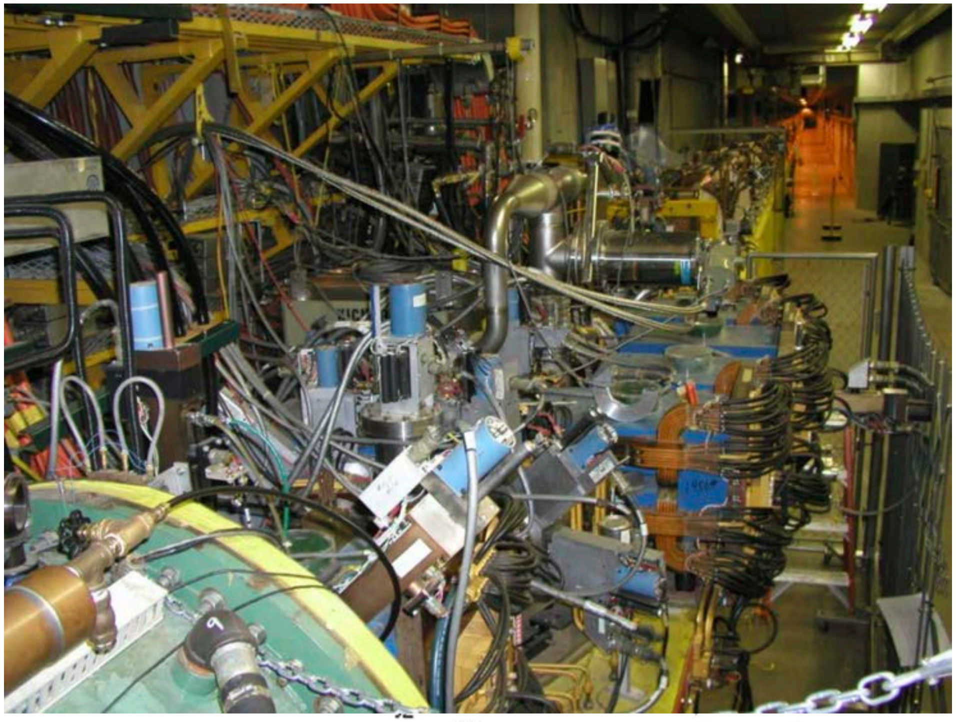
Bunch length at 70 MeV ~ 8°

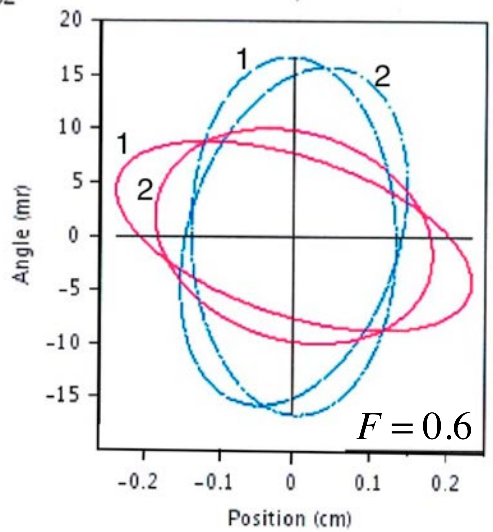
Longitudinal normalized beam emittance:

$4\varepsilon_{rms\_long}$ ~ 0.7 π cm mrad

Effect of Beam Mismatch at the Entrance of the DTL on Beam Loss in the Transition Region (100 MeV)







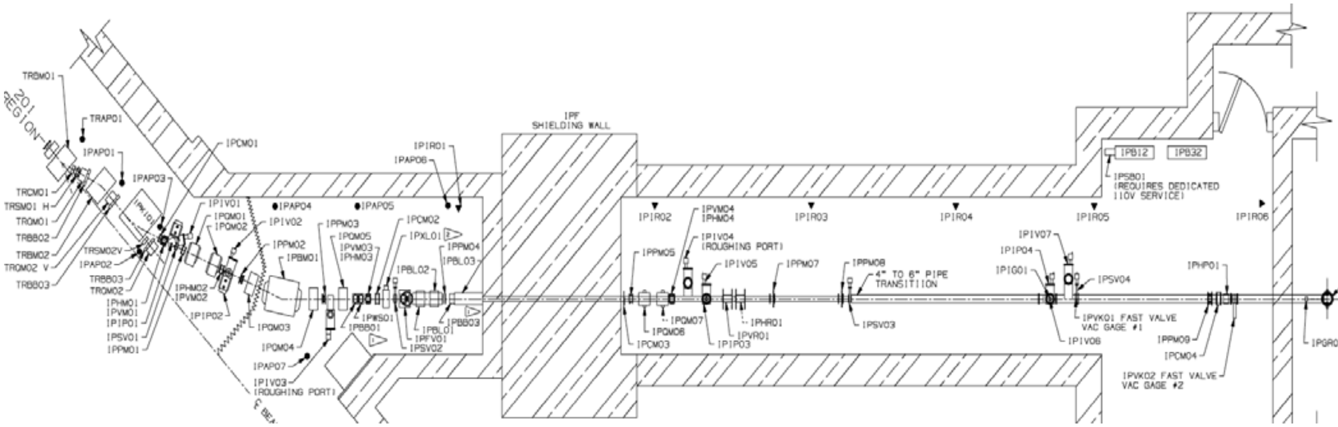
Mismatch Factor:

$$F = \sqrt{\frac{1}{2}(R + \sqrt{R^2 - 4})} - 1$$

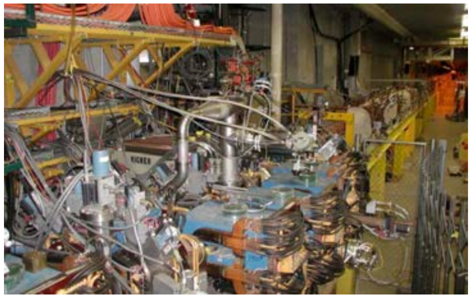
Ellipse Overlapping Parameter:

$$R = \beta_1\gamma_2 + \beta_1\gamma_2 - 2\alpha_1\alpha_2$$

Reduction of Beam Losses in the Isotope Production Facility



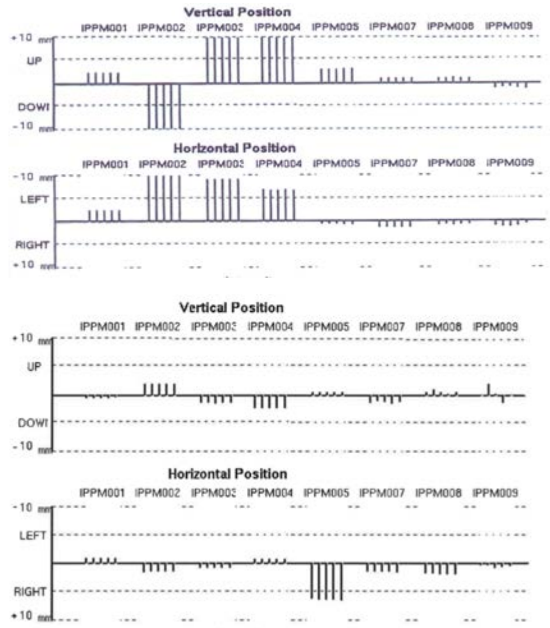
LANSCE Isotope Production Facility beamline.



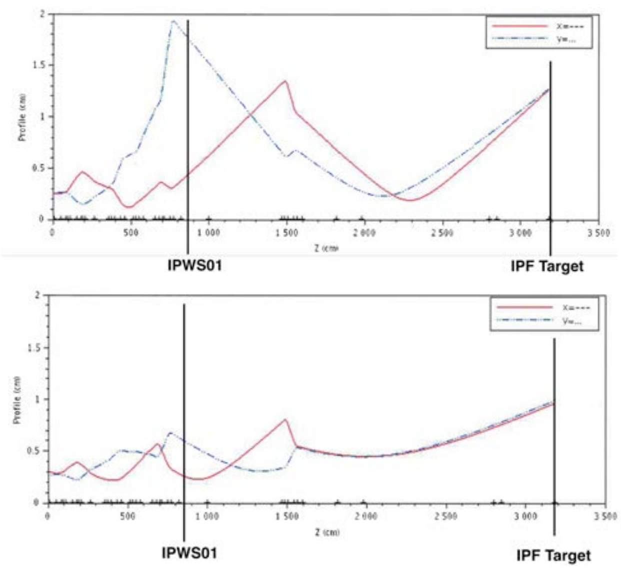
	H+ %
IPAP01	1
IPAP02	0
IPAP03	14
IPAP04	0
IPAP05	1
IPAP06	2

	H+ %
IPAP01	0
IPAP02	0
IPAP03	2
IPAP04	0
IPAP05	0
IPAP06	0

Activation Protection devices reading (a) before and (b) after retuning. Beam losses reduced from 4 x10^{-3} to 5 x10^{-4}.



Beam position monitors bar graph (a) before and (b) after beam based alignment.

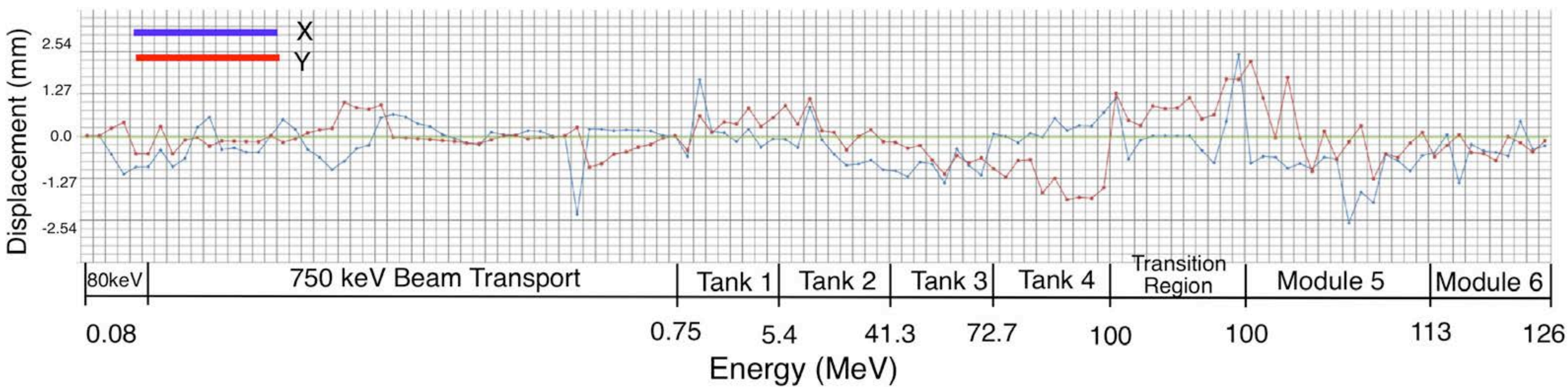


Beam envelopes (a) before and (b) after retuning of beamline.

Beam Emittance Growth in the CCL

Normalized rms beam emittance in CCL (π cm mrad)

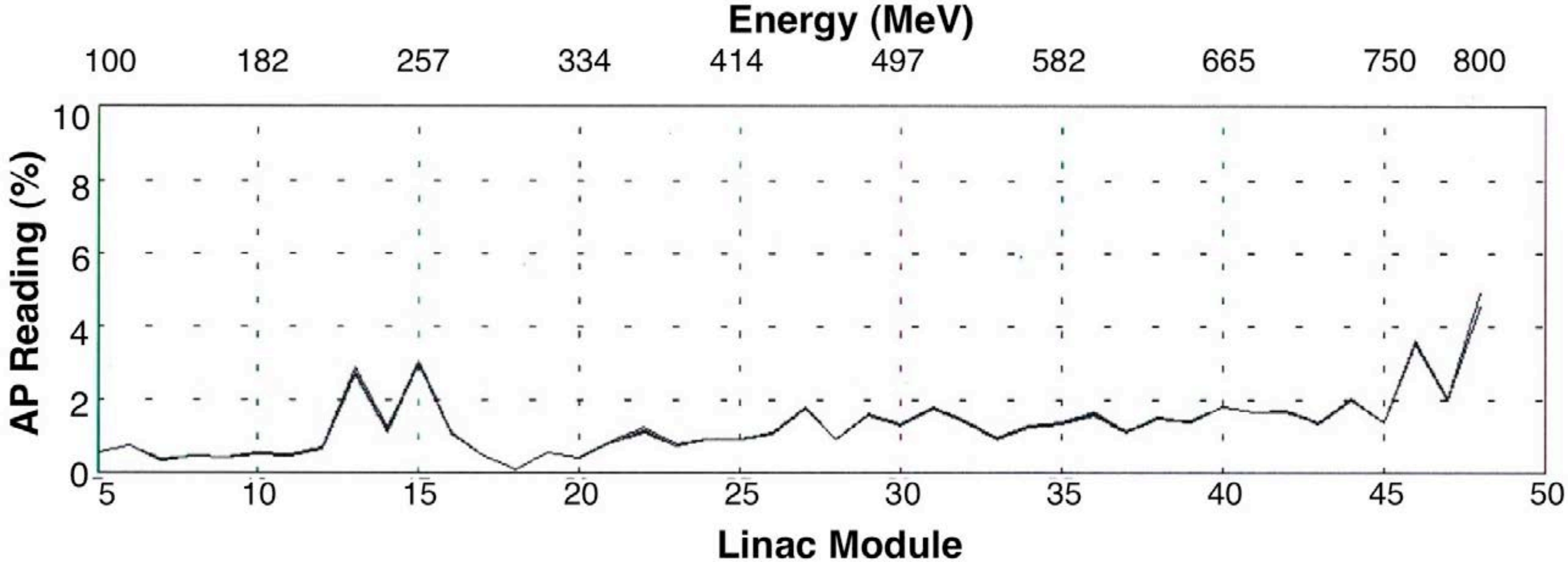
Energy	100 MeV	800 MeV
H^- (Lujan / pRad /UCN)	0.04	0.065
H^- (WNR)	0.058	0.124



Accelerator Misalignments

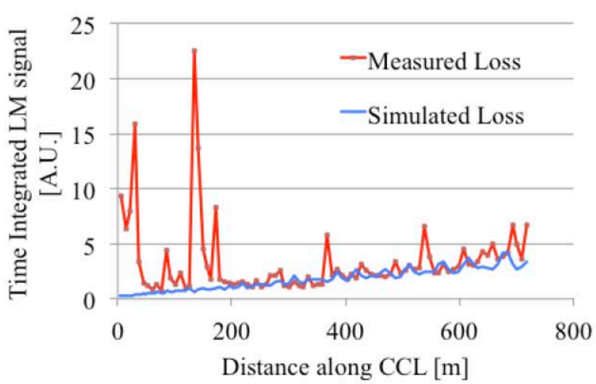
H^- Beam Losses in the Coupled Cavity Linac (100 MeV-800 MeV)

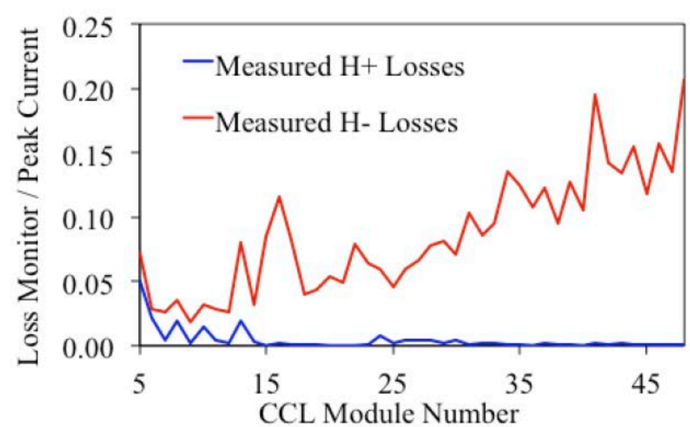
Beam losses in CCL: 0.1% - 0.2%



Previous study indicated significance of Intra Beam Stripping and Residual Gas Stripping on H^- beam losses in Coupled Cavity Linac (L.Rybarcyk, et al, IPAC12, THPPP067):

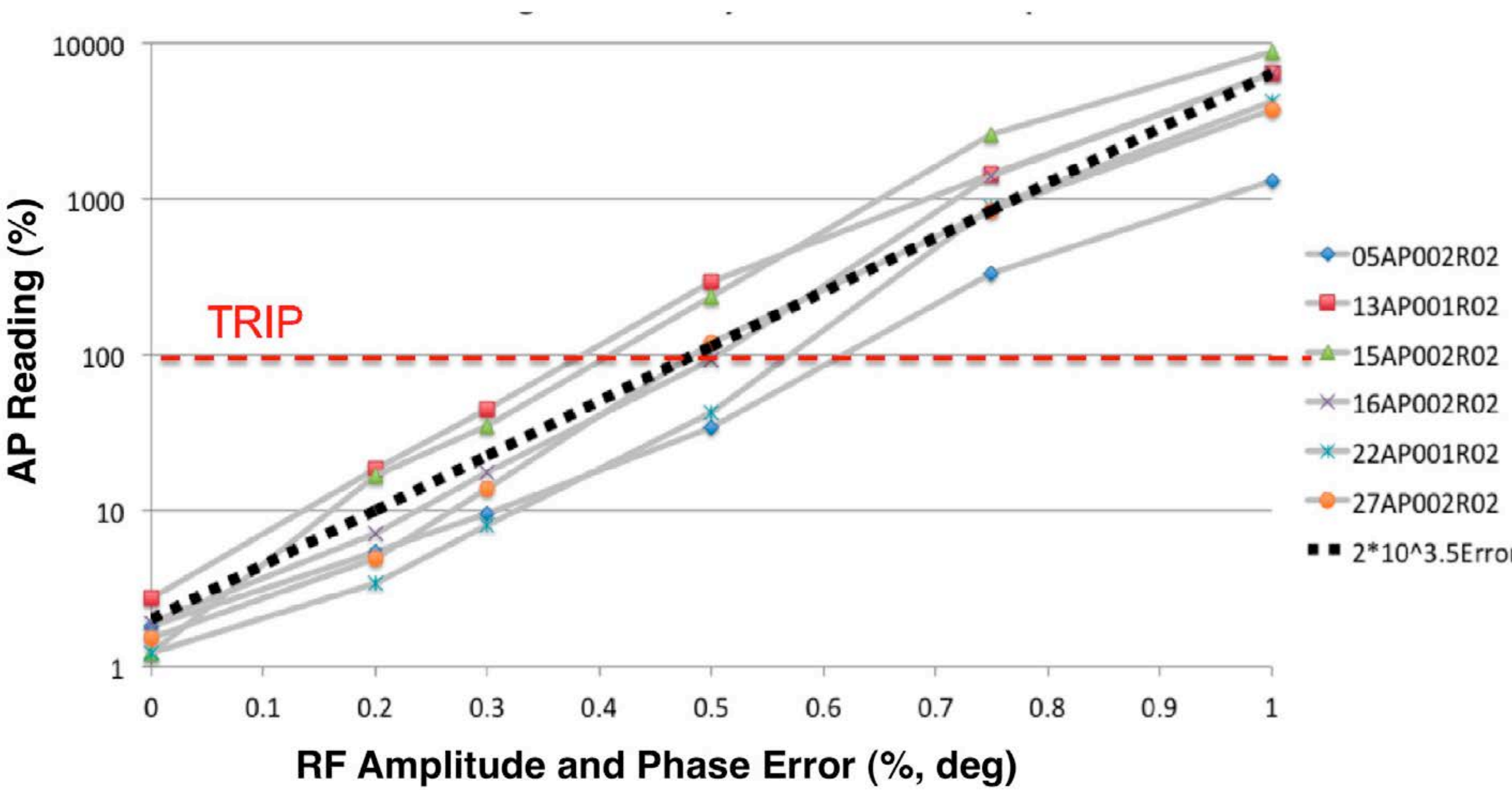
Stripping Mechanism	Beam Fractional Loss
Residual Gas Stripping	2×10^{-4}
Intrabeam Stripping	1.6×10^{-4}
Lorentz Field Stripping	4.5×10^{-11}





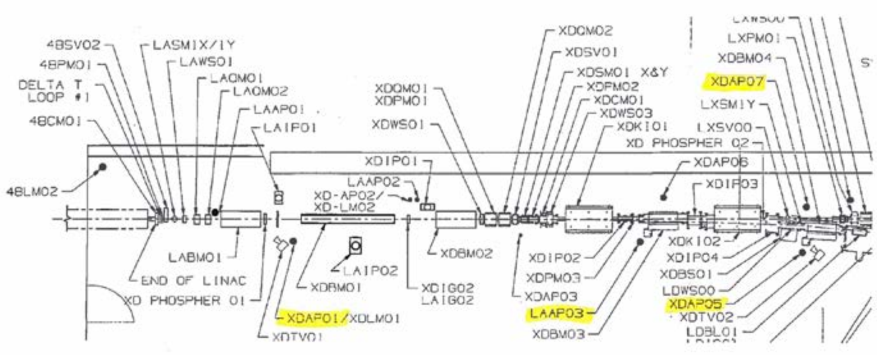
Effect of DTL Cavity Field Error on Beam Losses in the CCL

Maximum Spill ≈ $10^{n*Error}$ where n = 3 - 4

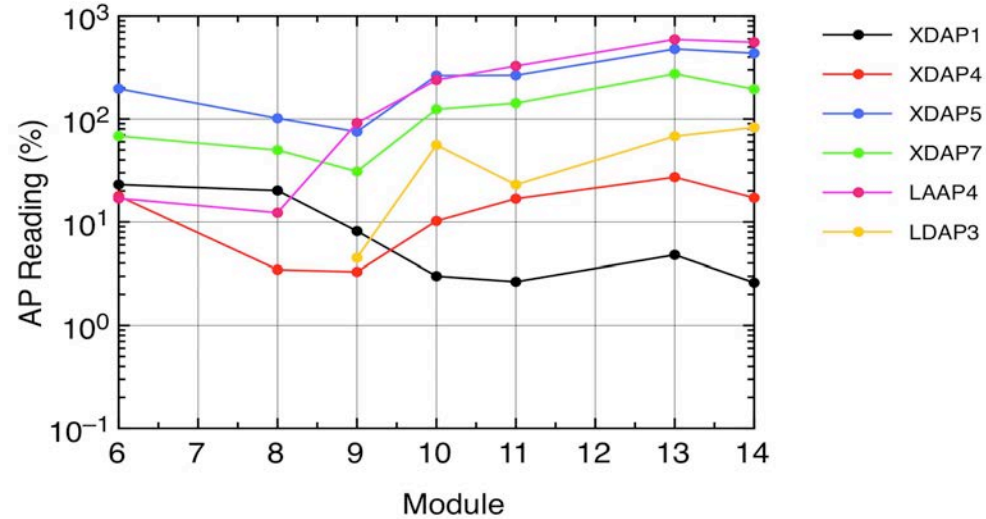


(L.Rybarcyk et al, LINAC 2016, MOPLR072)

Effect of 805 MHz Linac RF Stability on Beam Losses in the High-Energy Beamlines

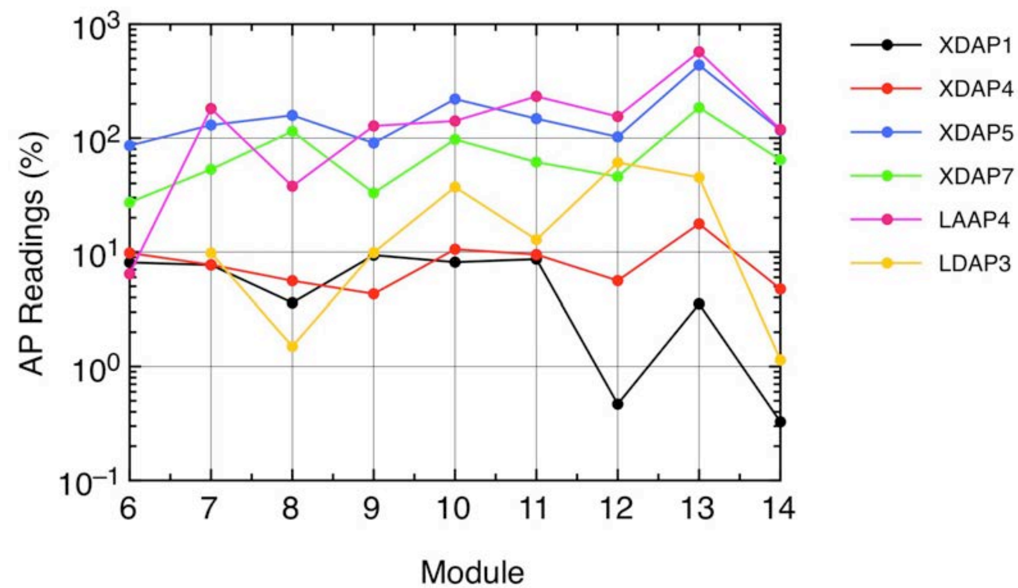


Location of Activation Protection devices in Switchyard



Beam spill normalized by 1% variation in RF amplitude.

The results of study confirm that the stability of the RF amplitudes and phases of 805 MHz linac should be kept within 0.1% and 0.1°, respectively, in order to provide safe operation of accelerator facility.



Beam spill normalized by 1° variation in RF phase.

(Y.Batygin, IPAC2018, TUPAL034)

Summary

1. LANSCE is a unique accelerator facility that simultaneously delivers beams to five experimental areas.

2. Multi-beam operation requires compromises in beam tuning to meet beam requirements at the different target areas while minimizing beam losses throughout the accelerator, proton storage ring, and beam transport lines.

3. Beam losses and emittance growth are controlled through careful beam matching along the accelerator, ion-source and LEBT adjustments, beam-based alignment, and improved RF phase and amplitude control.