An aerial photograph of the J-PARC (Japan Proton Accelerator Research Complex) facility. The image shows a large industrial and research complex with various buildings, parking lots, and green spaces. A river flows through the facility, and a large body of water is visible on the right side. The text is overlaid on the top half of the image.

# Measurement of continuous degradation of a stripper foil during six months operation with 300 kW beam power in the 3-GeV RCS of J-PARC

Pranab K. Saha

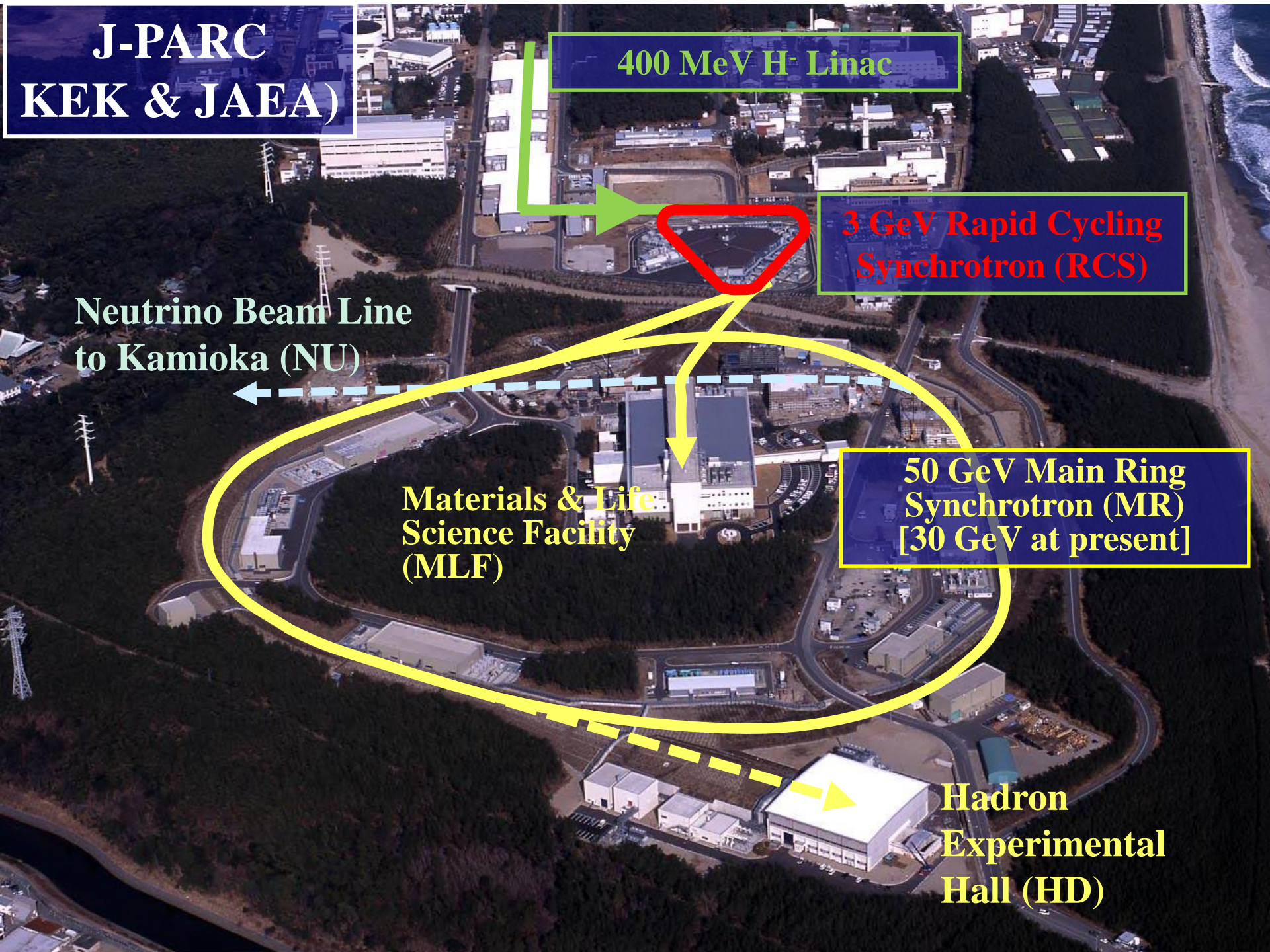
J-PARC, Japan

*INTDS conference @ Tokyo, Sept. 2014*

# Outline

## **Outline:**

- 1. Brief Overview of the RCS*
- 2. Motivation of the present study*
- 3. RCS Injection system and stripper foil*
- 4. Experimental principle and validity*
- 5. Experimental results and discussion*
- 6. Summary*



**J-PARC  
(KEK & JAEA)**

**400 MeV  $H^-$  Linac**

**3 GeV Rapid Cycling  
Synchrotron (RCS)**

**Neutrino Beam Line  
to Kamioka (NU)**

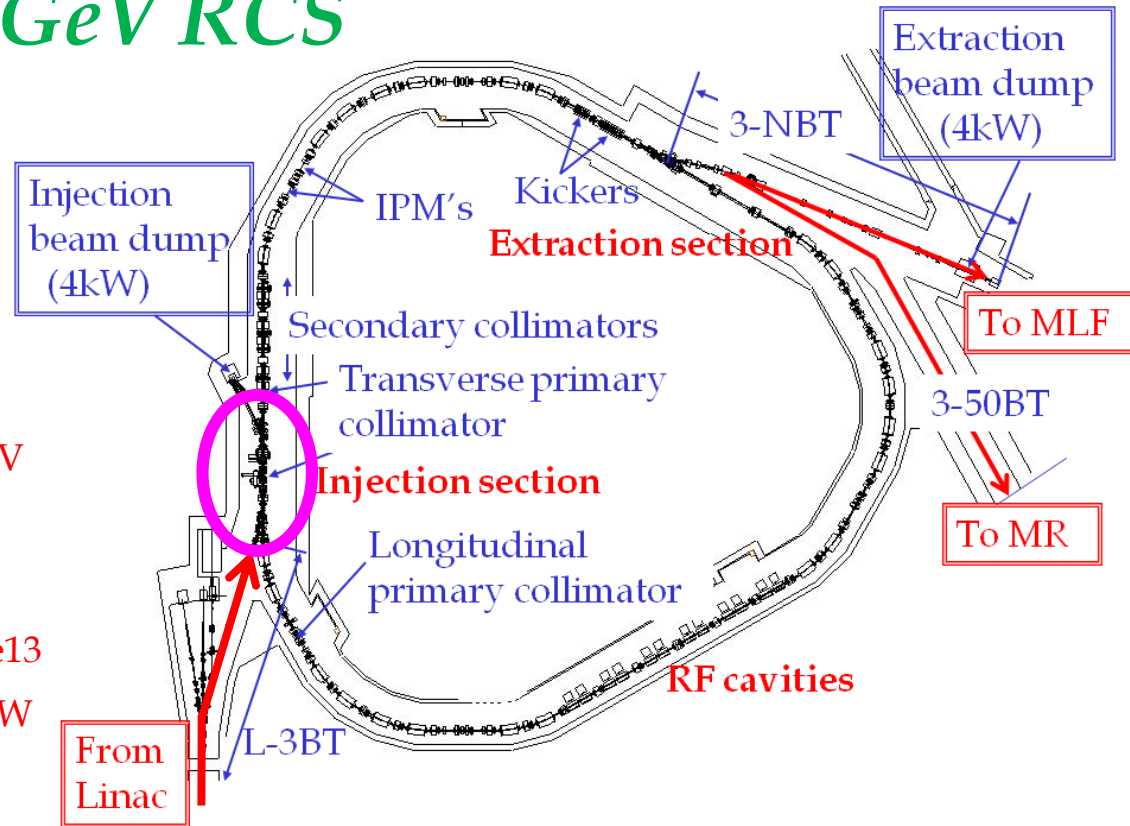
**50 GeV Main Ring  
Synchrotron (MR)  
[30 GeV at present]**

**Materials & Life  
Science Facility  
(MLF)**

**Hadron  
Experimental  
Hall (HD)**

# Overview of the 3-GeV RCS

Circumference	348.333 m
Superperiodicity	3
Harmonic number	2
No of bunch	2
Injection energy	181 MeV $\Rightarrow$ 400 MeV
Extraction energy	3 GeV
Repetition rate	25 Hz
Particles per pulse	$2.5 \times 10^{13} - 5 \times 10^{13} \Rightarrow 8.3 \times 10^{13}$
Output beam power	300–600 kW $\Rightarrow$ 1 MW
Transition gamma	9.14 GeV
Number of dipoles	24
quadrupoles	60 (7 families)
sextupoles	18 (3 families)
steerings	52
RF cavities	12 (11 at present)
Collimator Limit	4 kW( 3% @ injection for 1MW)



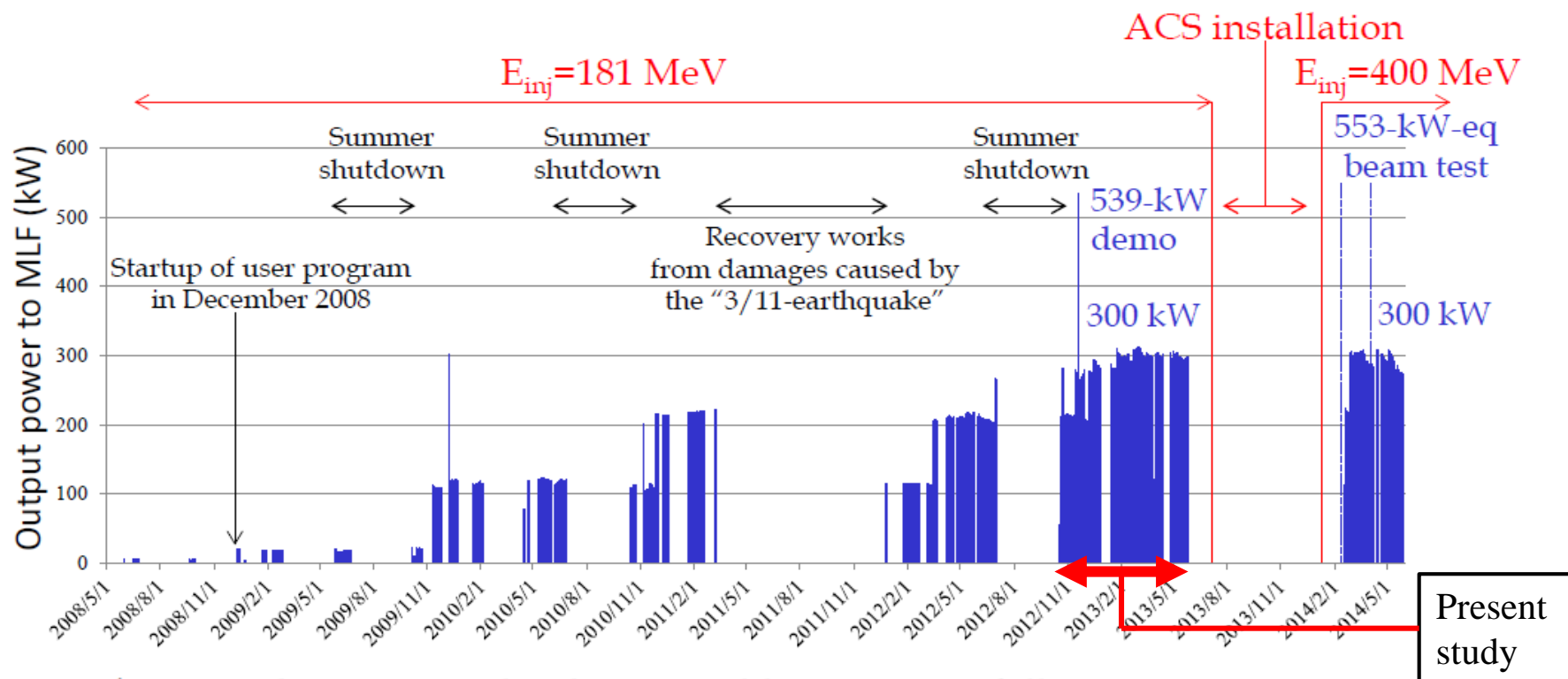
**Injection energy upgraded in 2013**  
**181 MeV  $\rightarrow$  400 MeV**

**Peak current: 30 mA  $\rightarrow$  50 mA**

**During 2014 summer shutdown period**  
 **$\rightarrow$  1 MW trial in Oct. 2014**

**1 MW user operation scheduled in 2015**

# History of RCS beam operation



- ✓ Output beam power has been steadily increasing following progression in the beam tuning & hardware improvements since startup of the user program in December 2008.
- ✓ Beam commissioning of RCS with  $E_{inj}=400$  MeV : January 2014~
- ✓ Re-startup of user program (300 kW output beam power) : February 2014~
- ✓ Successfully demonstrated high intensity beam trials up to 550 kW for both  $E_{inj}=181$  MeV and  $E_{inj}=400$  MeV.

# Motivation

A hybrid-type 20% Boron doped Carbon foil named **HBC foil** is used for **multi-turn  $H^-$  stripping injection** in the 3-GeV RCS of J-PARC.

Naturally, a long lifetime foil is desirable for stable operation at 1 MW.

However, a complete failure is not always a lifetime as foil degradation such as foil thinning and pinhole formation caused by the beam irradiation increases the waste beam so as the heat load on the dump.

**The waste beam dump capacity is only 4 kW.**

A foil thickening on the other hand increases the foil scattering beam loss.

**One has to replace the foil with a new one and that limits the lifetime.**

*A foil degradation could be a foil breaking signal but the degradation scenario could be different for different foil type.*

*An accurate monitoring can thus provide important information on the foil breaking mechanism.*

It can also determine an appropriate foil replacement time so as to avoid foil failure during operation.

# RCS $H^-$ stripping injection system

3 strippers foils, Type: HBC

Primary (1<sup>st</sup>)@400 MeV:  $340 \mu\text{g}/\text{cm}^2$

@181 MeV:  $200 \mu\text{g}/\text{cm}^2$

Stripping efficiency: 99.7%

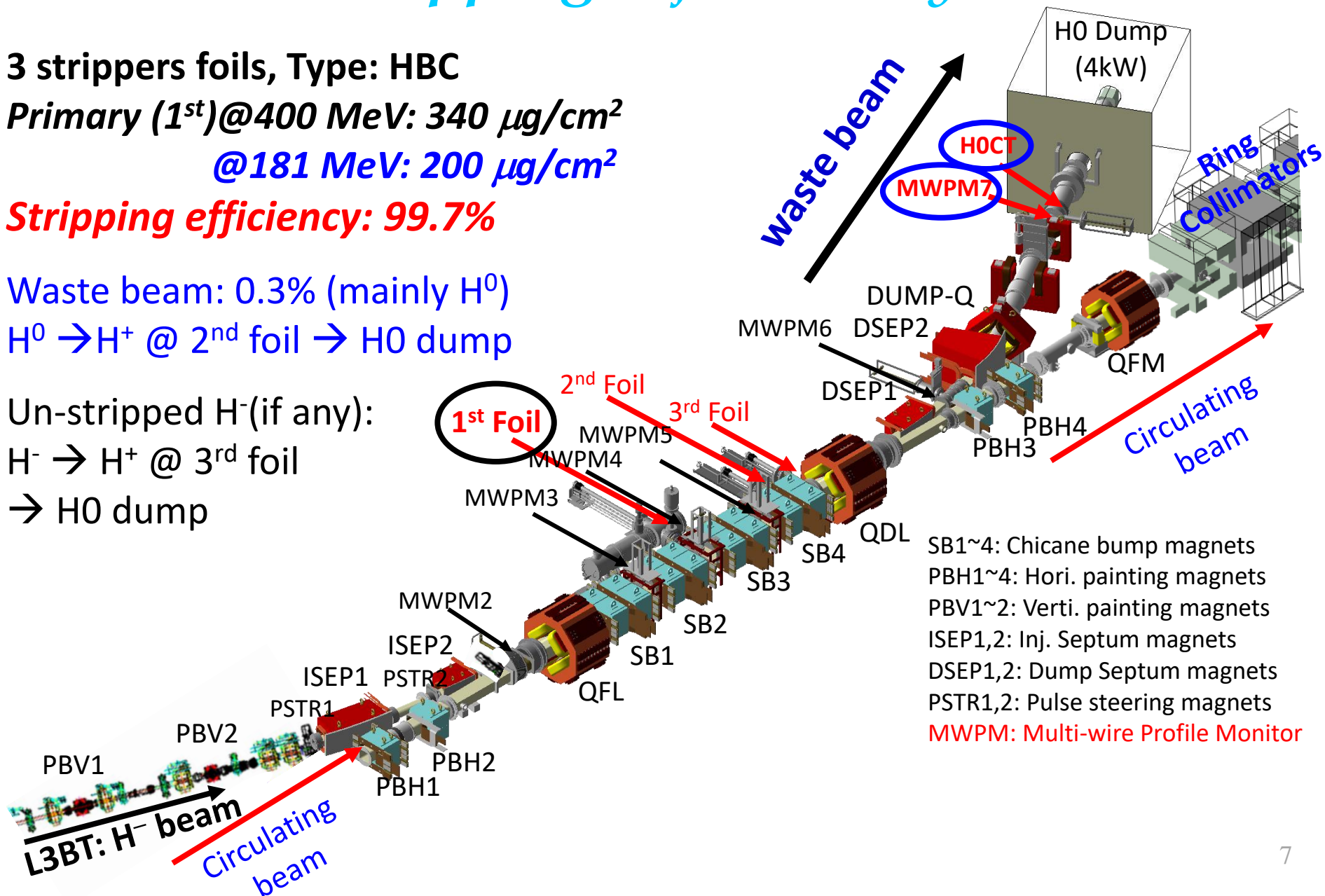
Waste beam: 0.3% (mainly  $H^0$ )

$H^0 \rightarrow H^+ @ 2^{\text{nd}} \text{ foil} \rightarrow H^0 \text{ dump}$

Un-stripped  $H^-$ (if any):

$H^- \rightarrow H^+ @ 3^{\text{rd}} \text{ foil}$

$\rightarrow H^0 \text{ dump}$



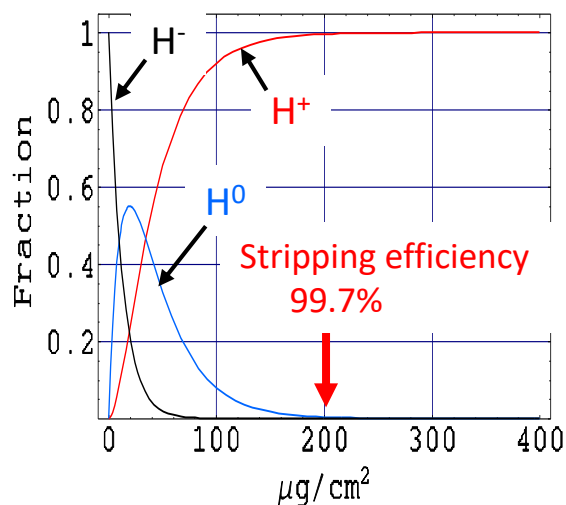
## 2. Foil thickness vs. Stripping efficiency

### Parameter list

Energy (MeV)	400	181
Foil thickness ( $\mu\text{g}/\text{cm}^2$ )	333	200
Stripping efficiency (%)	99.7	99.7
Waste beam fraction (%)	0.3	0.3
Inj. Beam power max (kW)	133	36
Waste beam power (kW)	0.4	0.14
Dump limit (kW)	4	4

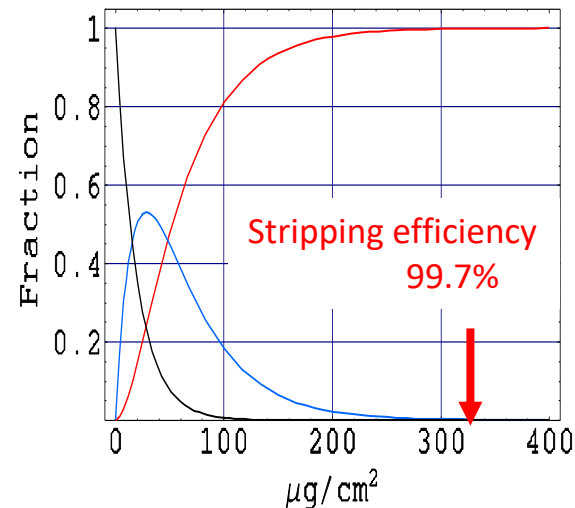
R.C. Webber et. al.  
IEEE. Nucl. Sci. NS-26(1979)

$E_{\text{inj}} = 181 \text{ MeV}$



W.Chou et. al.  
NIM A 590 (2008)

$E_{\text{inj}} = 400 \text{ MeV}$

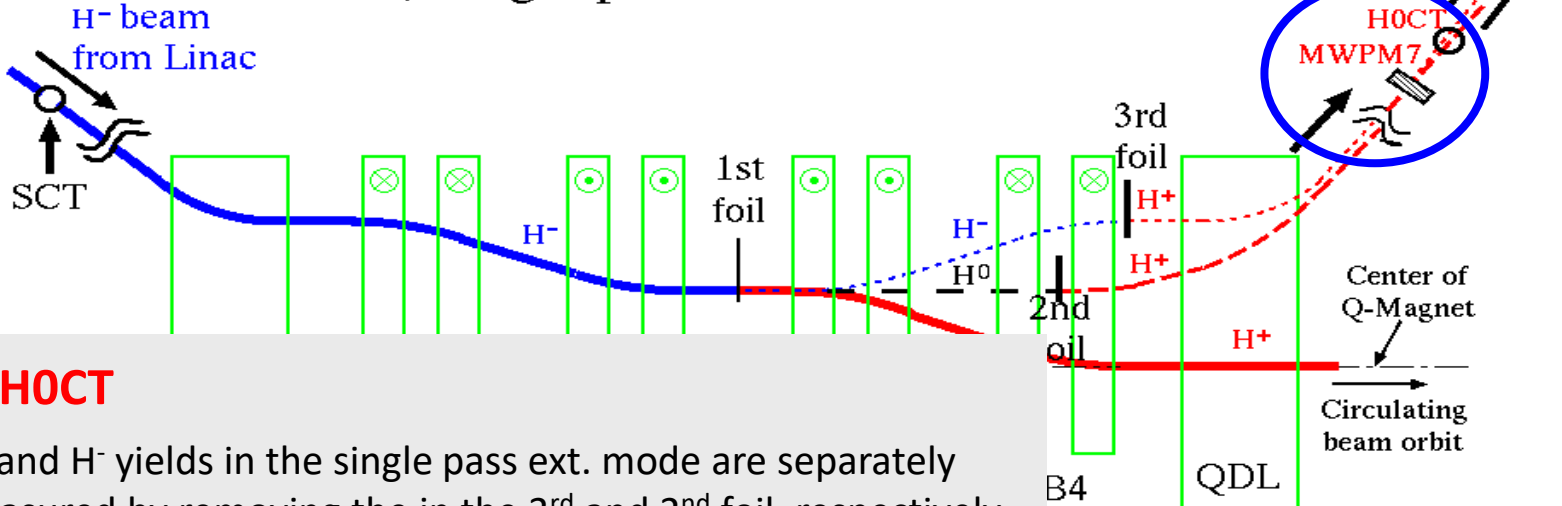


**Thicker foil** → increases stripping efficiency  
but it increases foil scattering beam loss too.

**Thinner foil** → increase the waste beam  
 ■ Needs larger dump → require space and money  
 ■ Maintenance of injection area gets difficult

## Measurement principle

### a) Single-pass extraction mode



# 1. НОСТ

$H^0$  and  $H^-$  yields in the single pass ext. mode are separately measured by removing the in the 3<sup>rd</sup> and 2<sup>nd</sup> foil, respectively.

## 2. MWPM7

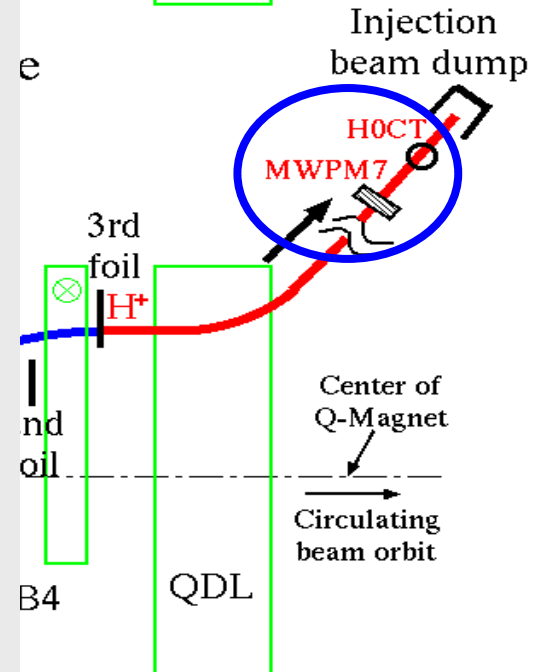
H<sup>0</sup> and H<sup>-</sup> yields can be simultaneously measured by the MWPM7 as two profiles are more than 70 mm apart.

$$H^0 \text{ fraction} = H^0 \text{ yield (a)} / \text{Total yield (b)}$$

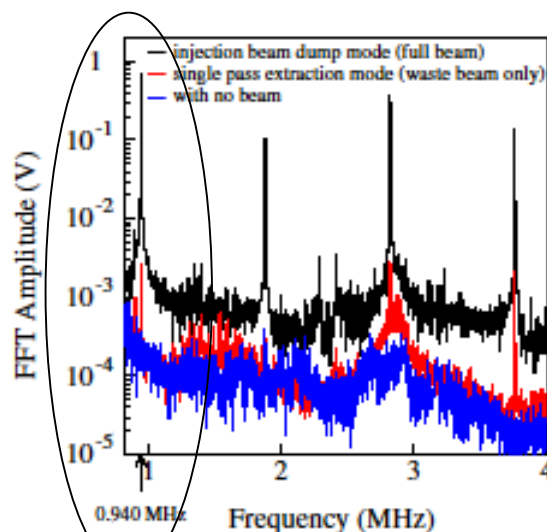
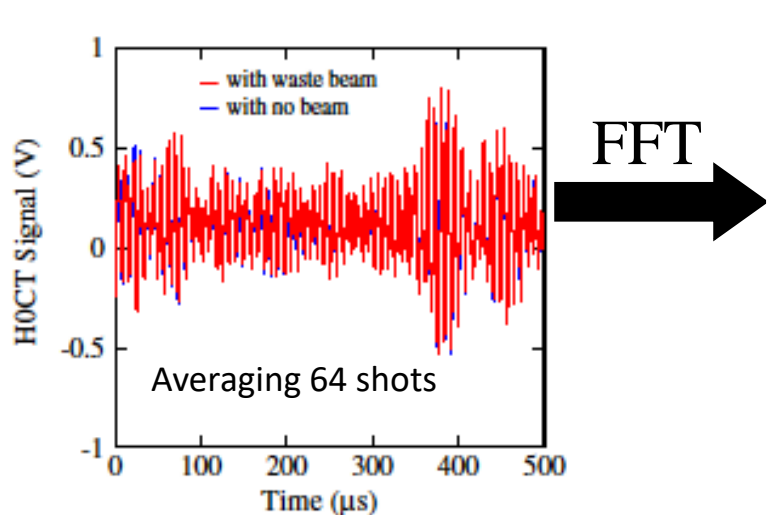
$$H^- \text{ fraction} = H^- \text{ yield (a)} / \text{Total yield (b)}$$

Where, a and b denote operation modes.

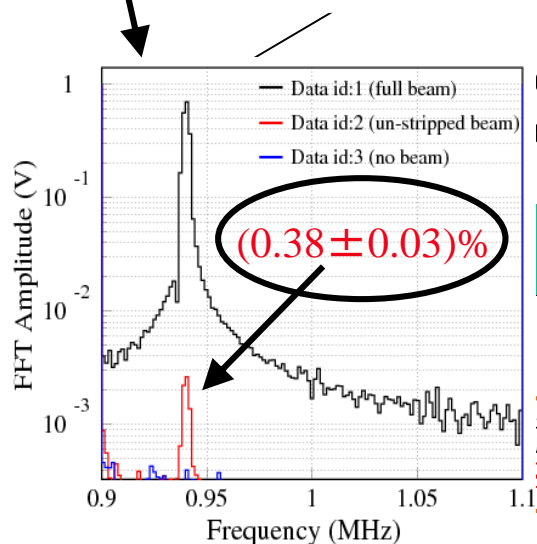
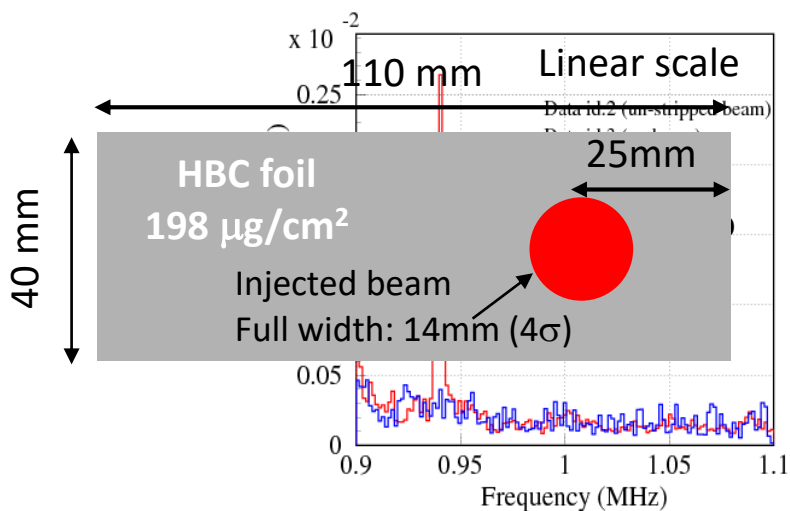
- Increasing /decreasing  $H^0$  fraction  
→ *Foil thinning/thickening*
- Increasing  $H^-$  fraction  
→ *Pinhole formation, foil deformation, etc..*



# Measurement technique: H0CT



Typical waste beam signal measured by a CT  
**Very identical w/ beam and w/ no beam**  
 → Hard to extract real information

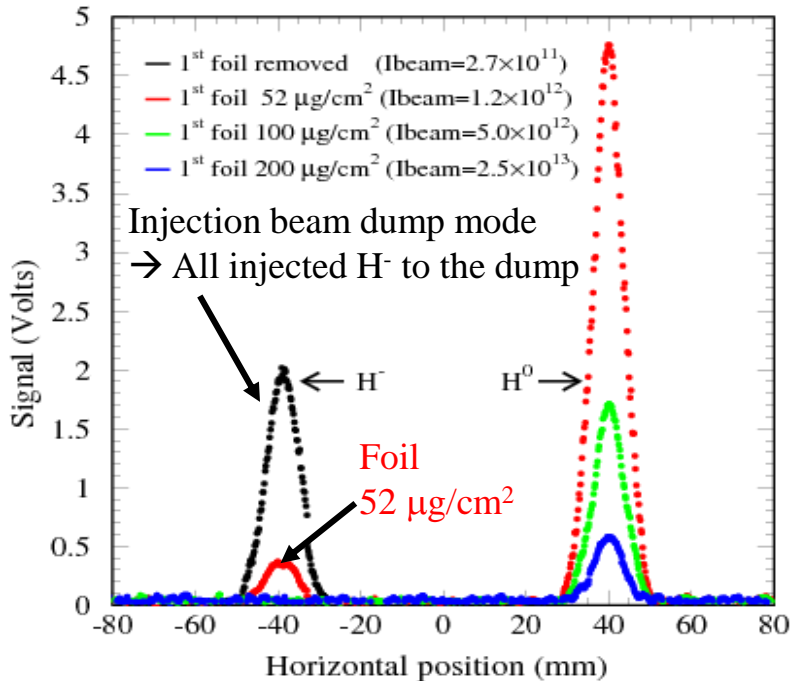


Injection pulse & dump

*P.K. Saha et al.*  
*PRST-AB 14, 072801 (2011)*

Injection  
 940 MHz

# Measurement by MWPM7



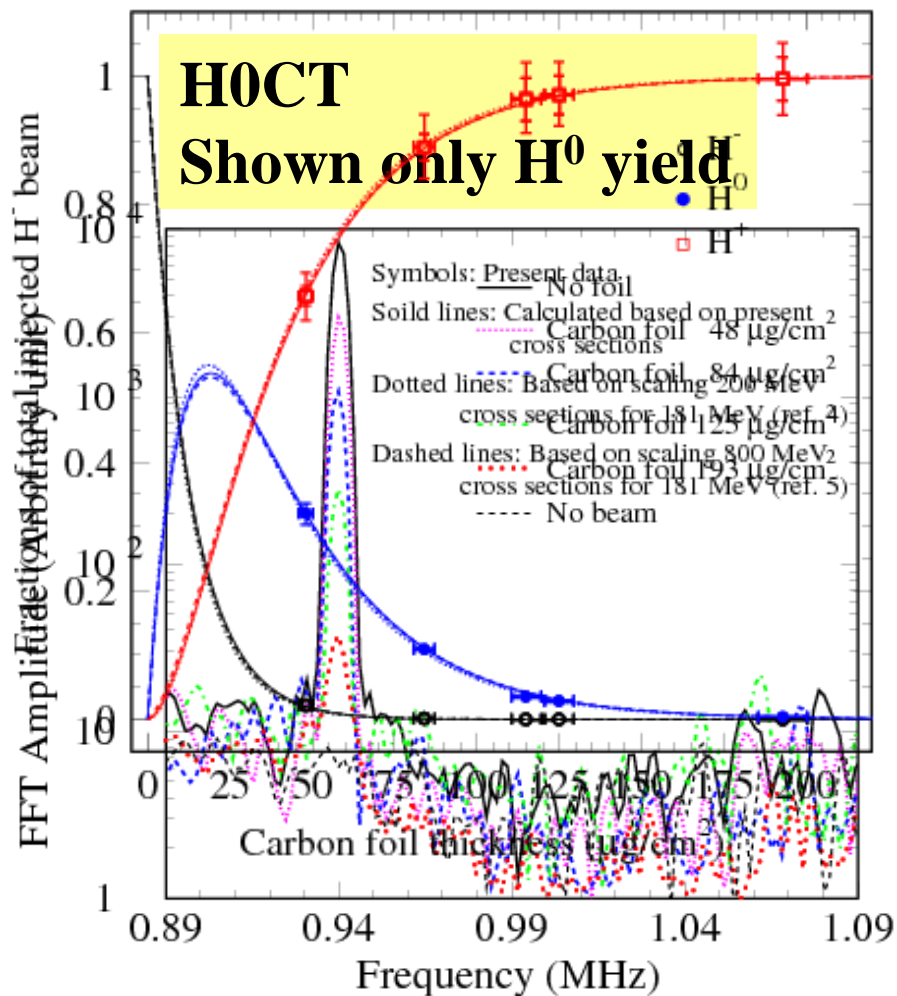
$\text{H}^0$  and  $\text{H}^-$  yields can be simultaneously by MWPM7.

The  $\text{H}^0$  and  $\text{H}^-$  fractions are obtained by normalizing their yields by the  $\text{H}^-$  yield measured in the injection beam dump mode.

The results were consistent with H0CT measurements.

*Injected beam intensity is controlled so that profile doesn't saturate.  
 For Injection dump mode  $I_{\text{beam}}$  is 1/100 of full intensity.*

# Measurement of 181 MeV $H^-$ stripping cross sections by carbon foil



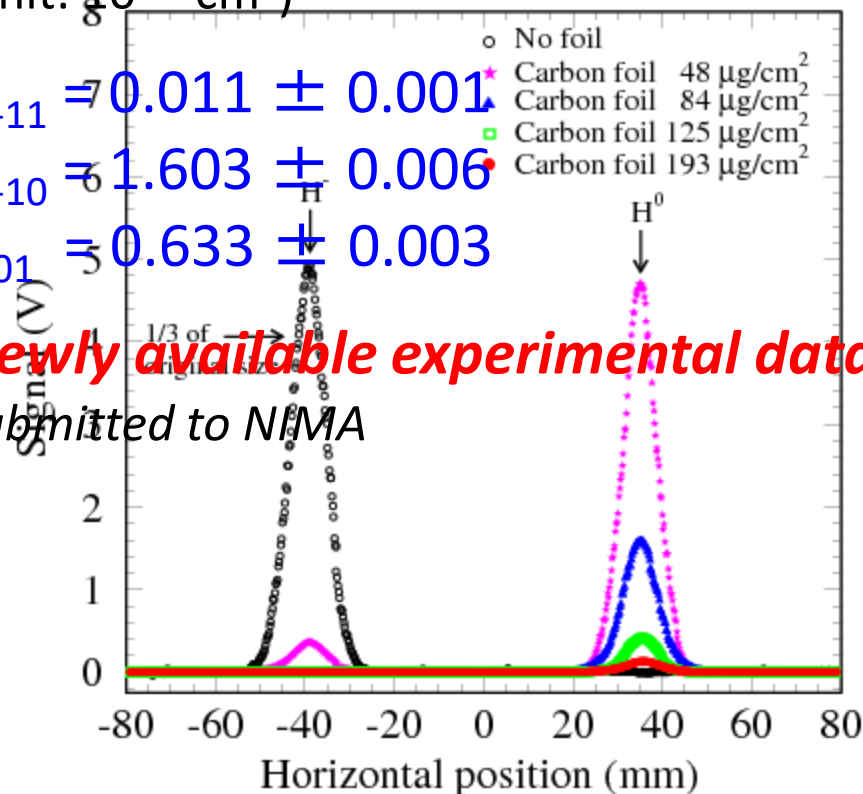
**MWPM7**  
Measured cross section  
(unit:  $10^{-18} \text{ cm}^2$ )

$$\sigma_{-11} = 0.011 \pm 0.001$$

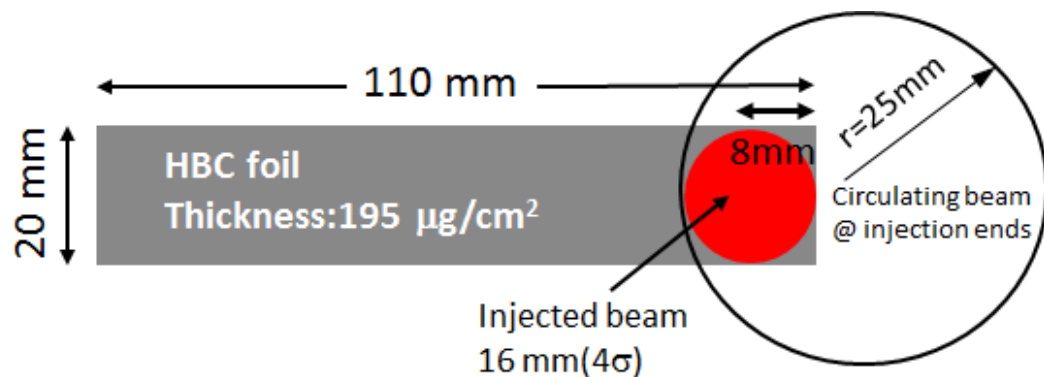
$$\sigma_{-10} = 1.603 \pm 0.006$$

$$\sigma_{01} = 0.633 \pm 0.003$$

**Newly available experimental data!**  
Submitted to NIMA



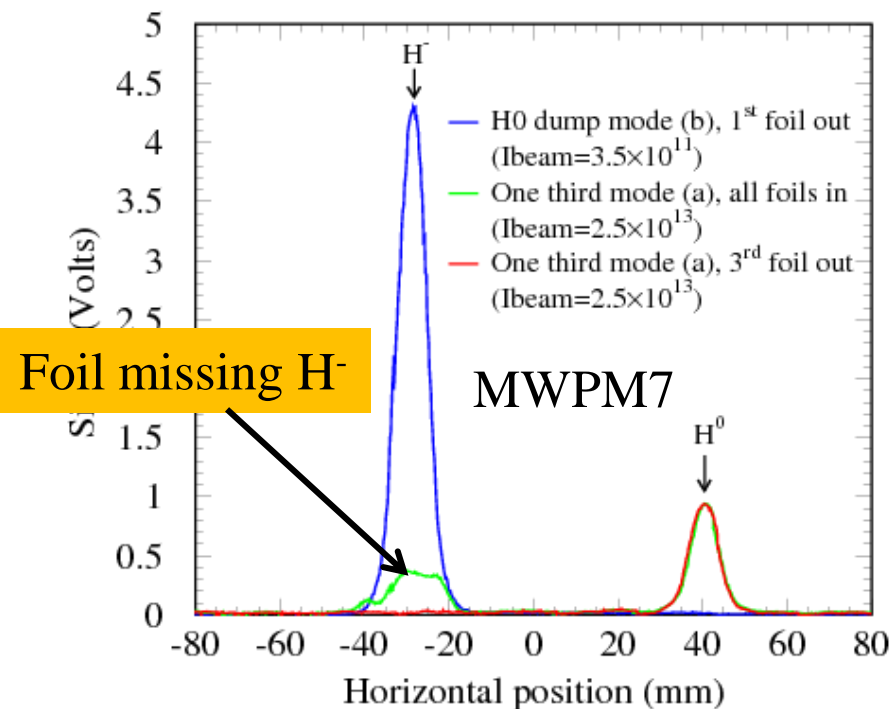
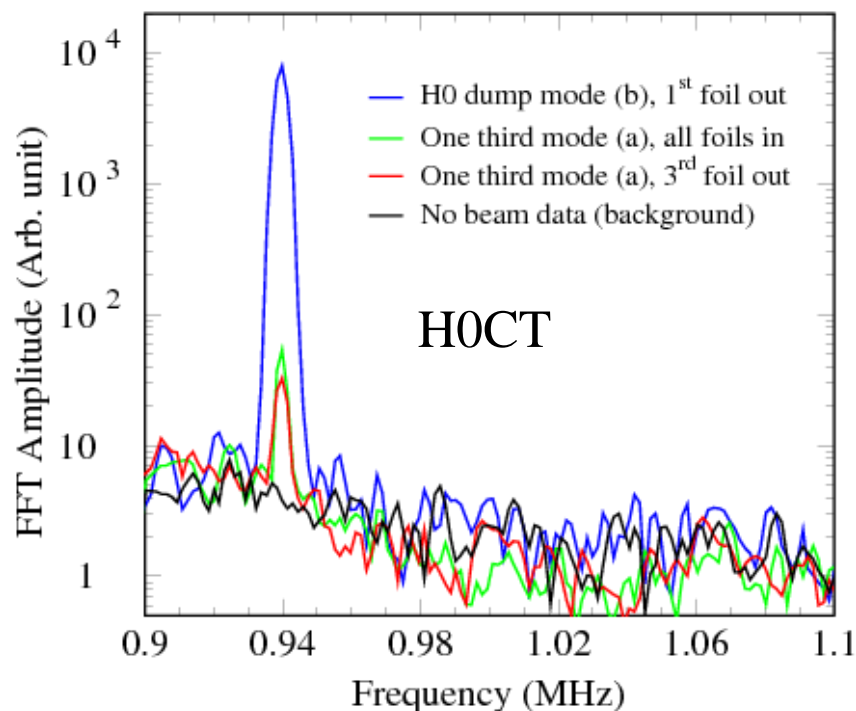
# Experiment results of the foil degradation during operation



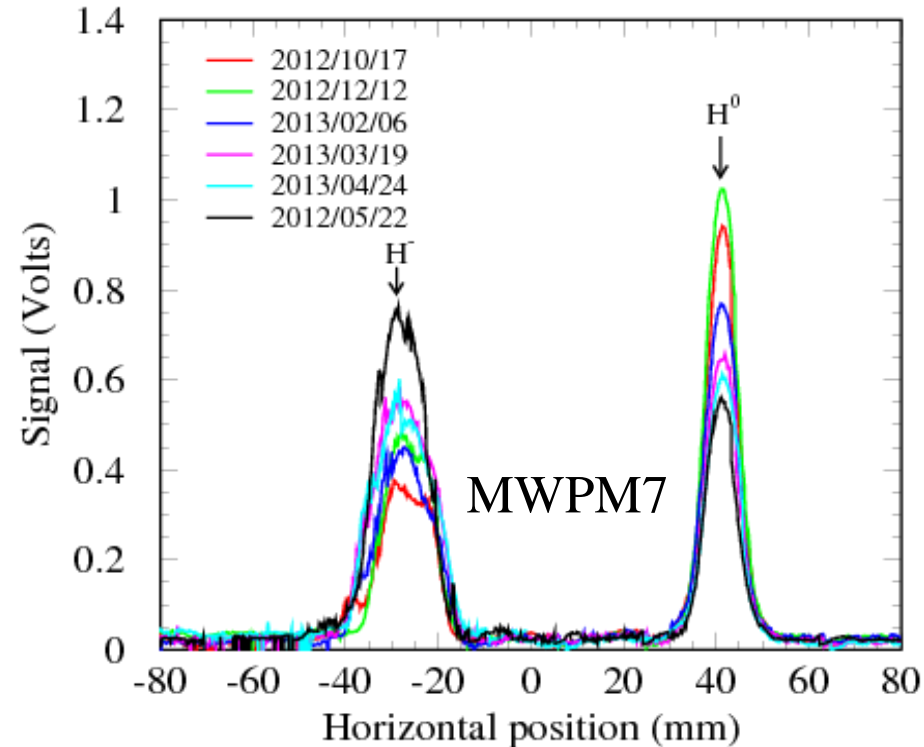
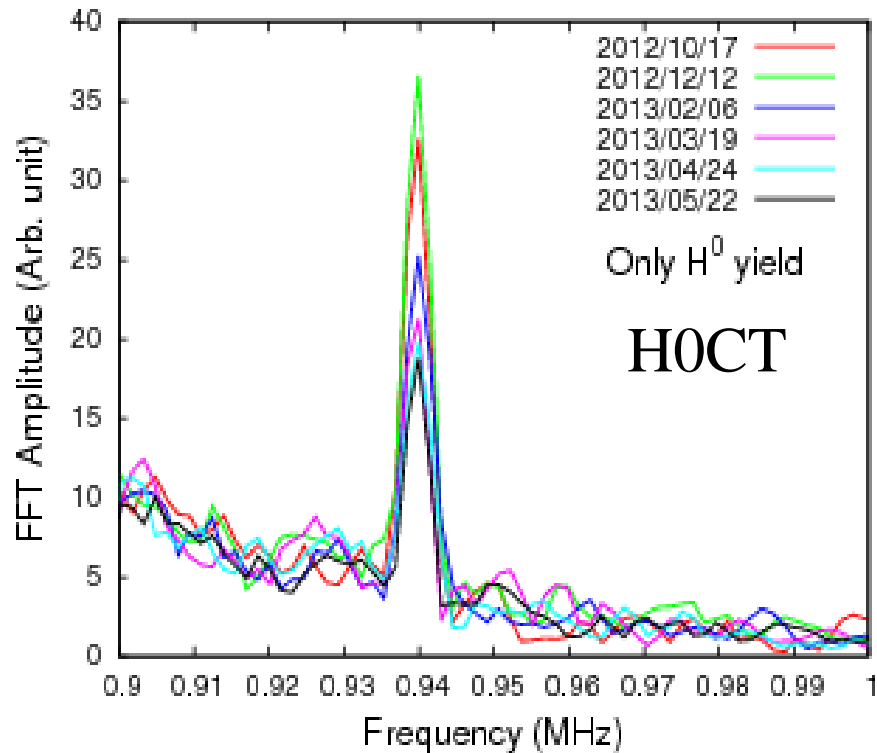
**Foil thickness: 1st measurement**

**H0CT :  $195 \pm 1.8 \mu\text{g}/\text{cm}^2$**

**MWPM7:  $196 \pm 2.7 \mu\text{g}/\text{cm}^2$**

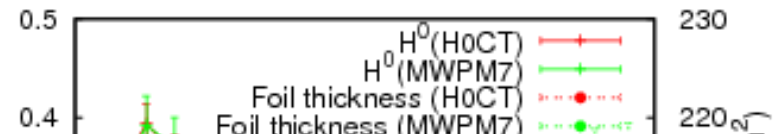
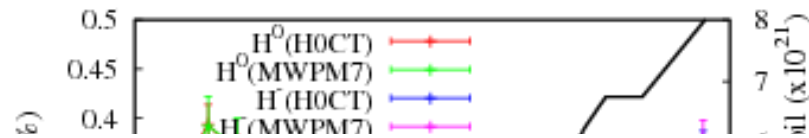


# Trend of the $H^0$ and foil missing $H^-$ yields during 6 months operation



- $H^0$  was measured to be continuously decreased.  
→ *Foil thickening!!*
- However, foil missing  $H^-$  was gradually increased  
→ *Foil deformation, pinhole, shrinkage, curling.....*

# Analysis of the foil degradation

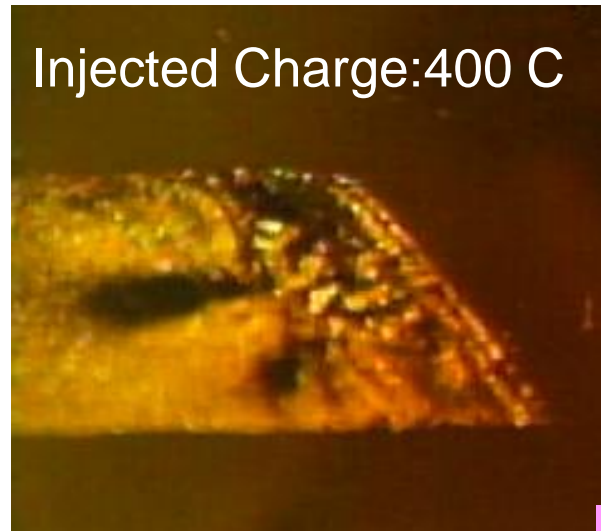
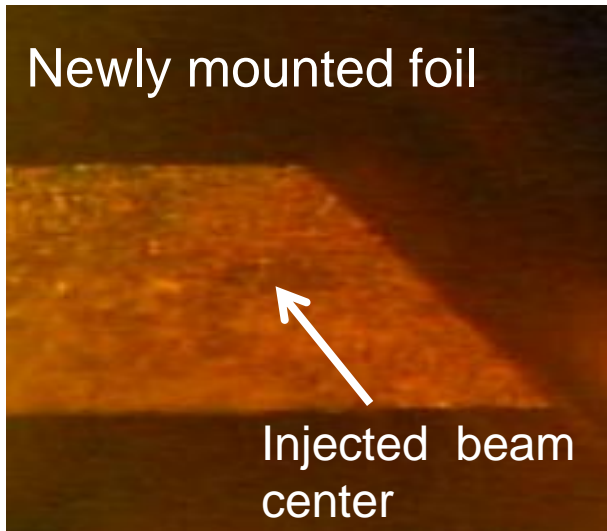


## Photographs of foil in use

Oct. 17, 2012

Dec. 27, 2012

May 22, 2013



**$195 \mu\text{g}/\text{cm}^2 \rightarrow 216 \mu\text{g}/\text{cm}^2$ .**

Avg. hit of each injected proton: ~20  
→ Total charge on the foil × 20

The un-stripped H<sup>-</sup> was gradually increased may be because of foil deformation gradually getting worse?

**Nevertheless, the foil last for 7 months and still survived!**

# Observation of foil thickening: Past Los Alamos PSR data

Courtesy:  
T. Spickermann, HB 2008 WS  
R. Macek, Los Alamos

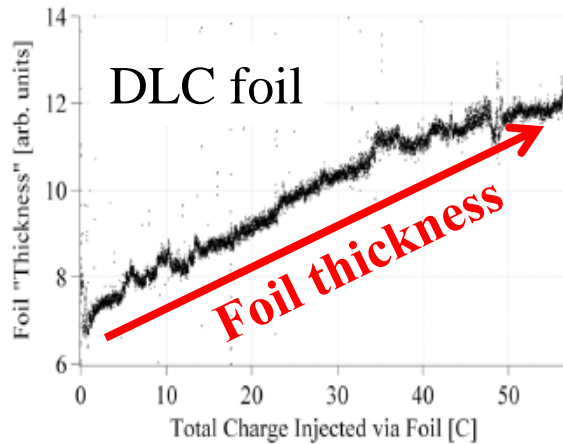


Figure 5: The foil "thickness" variable, obtained by dividing a foil scattering loss signal by the foil current, changed dramatically within two weeks for the DLC foil, indicating strong wrinkling or curling.

LANL foil:  
Developed at KEK & LANL



Figure 1: Photograph of a LANL foil newly mounted on the frame (left) and of a foil after several weeks of beam exposure (right).

NC foil: Developed at SNS



Figure 2: Photograph of an NC foil before installation in PSR (left) and of a foil after several weeks of beam exposure (right).

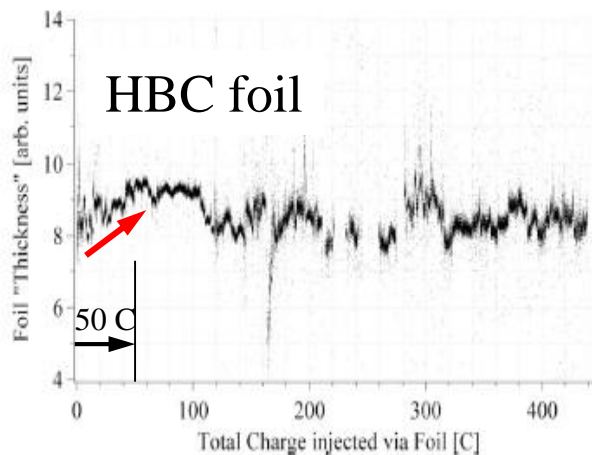
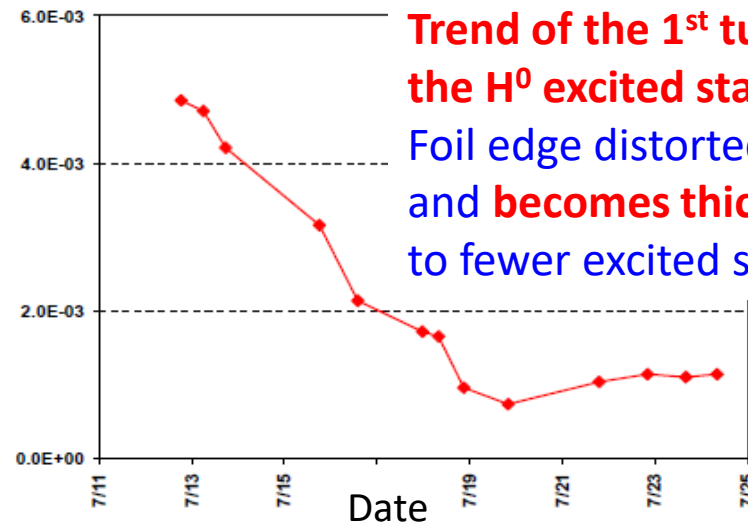


Figure 7: The foil "thickness" variable for the HBC foil does not yet indicate any deterioration.

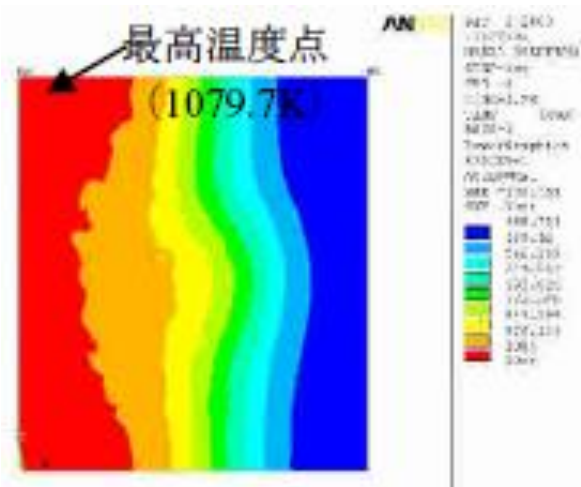
"1st Turn" Loss Rate (per proton) for 200  $\mu\text{g}/\text{cm}^2$  foil (1992)



**Trend of the 1<sup>st</sup> turn loss from the  $H^0$  excited states**

Foil edge distorted with time and **becomes thicker** leading to fewer excited states.

# Operation scenario at 1 MW



*Kuramochi et al.*

*The 14<sup>th</sup> Symp. on Acc. Sci. and Tech.  
Tsukuba, Japan 2003*

ACCSIM + ANSYS

**Peak temperature: 1079 K**

However, depending on foil edge margin and injection bump falling speed, peak foil temperature could be **>> 1500 K**

**At present w/ 300 kW operation: ~600 K**

● During the present study, injected beam power was only 18 kW (15% of the design 133 kW at 1MW).

● Foil degradation rate would be much faster at 1MW due to foil peak temperature rising much higher.

*Because, there was no such a foil degradation as we measured for comparatively a lower beam power (INTDS 2012)*

**Foil degradation even a little is very crucial at 1MW!**

● 15 foils can be mounted in a foil magazine.

One foil should last for at least 2 weeks.

(2 weeks × 15 foils ~7 months)

To ensure re

**It may be interesting to study other foil types!**

# Summary

We have established an efficient measurement techniques for monitoring foil degradation during accelerator operation.

An absolute change of the foil thickness is accurately measured.

*The foil is measured to be gradually thickening and it was more than 10% at the end of six months operation.*

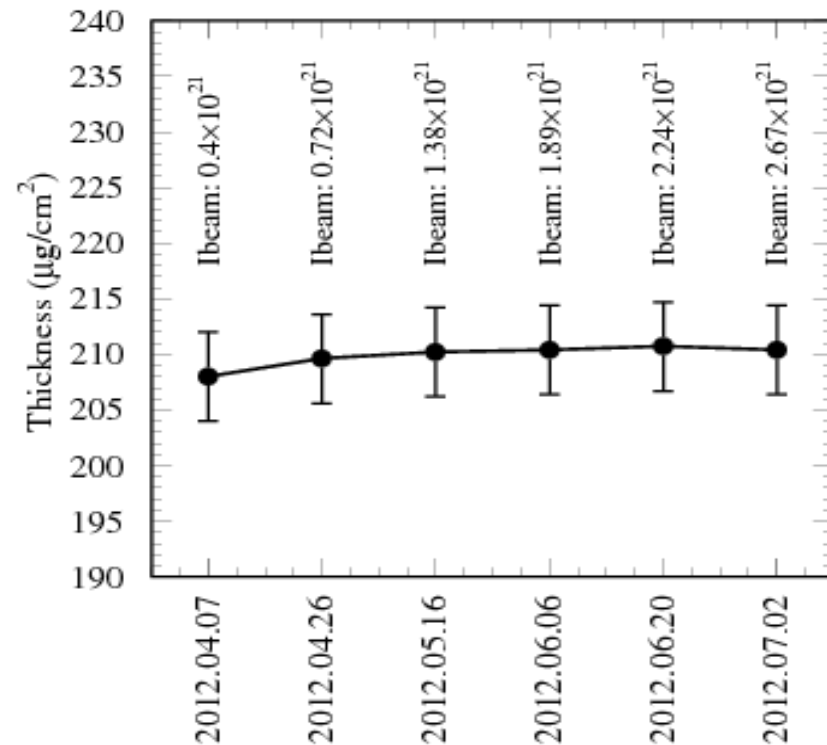
*However, there was no clear indication on the pinhole formation yet.*

We will continue the measurement with present 400 MeV injection and also planned to measure an intensity dependence of the foil degradation rate.

*The present study may provides important information on the foil breaking mechanisms and can also play an important role to ensure best uses of the stripper foils at 1 MW operation.*

***Extra slides***

# INTDS 2012: Foil thickness trend

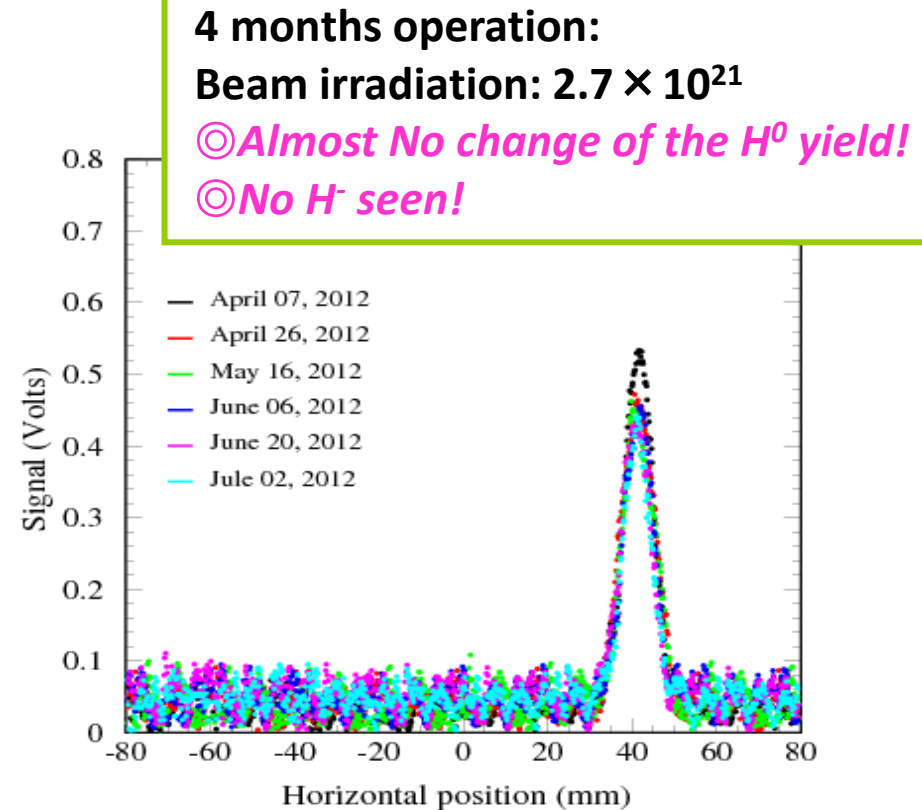


Measurement error:  $\pm 2\%$  in thickness

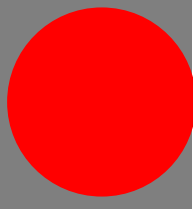
■ *No observable foil degradation so far!*

There was no any missing H- throughout the end.

■ *Thickness increases a little ( $\sim 1\%$ ) in the beginning.*



Foil: HBC  
110 x 30 mm<sup>2</sup>  
348  $\mu\text{g}/\text{cm}^2$

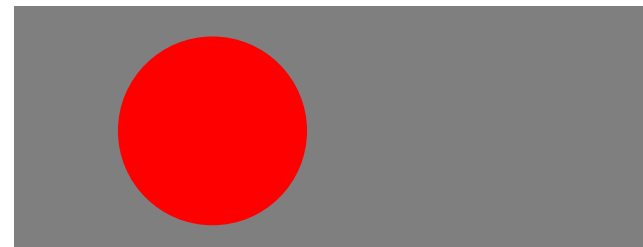


12mm

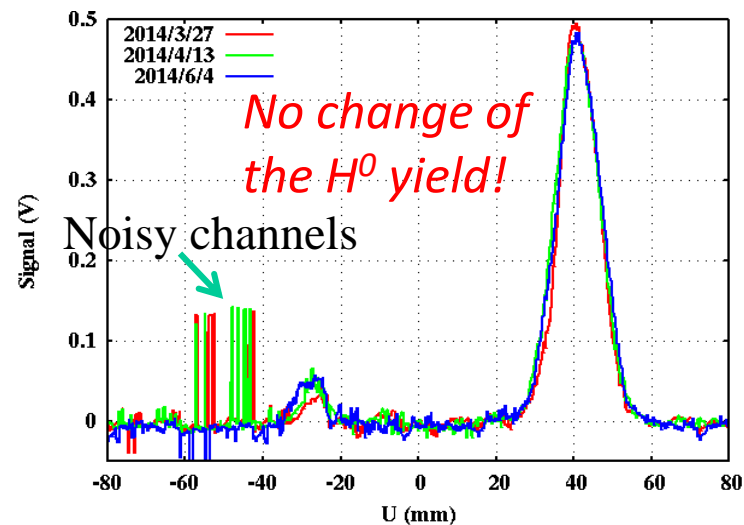
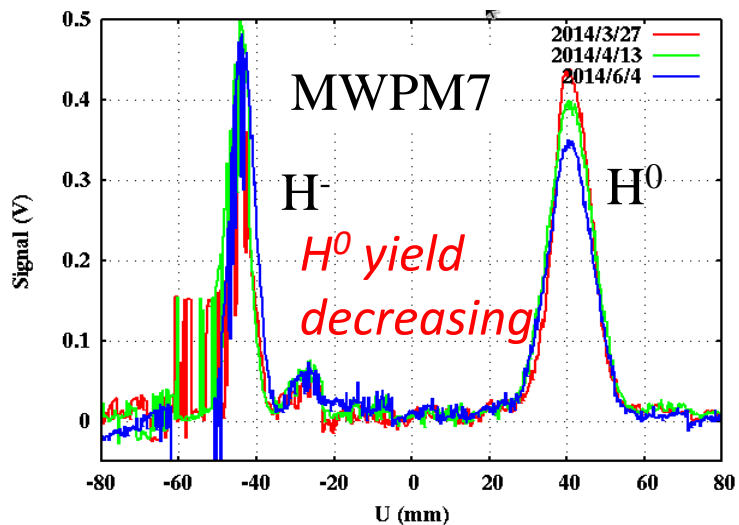
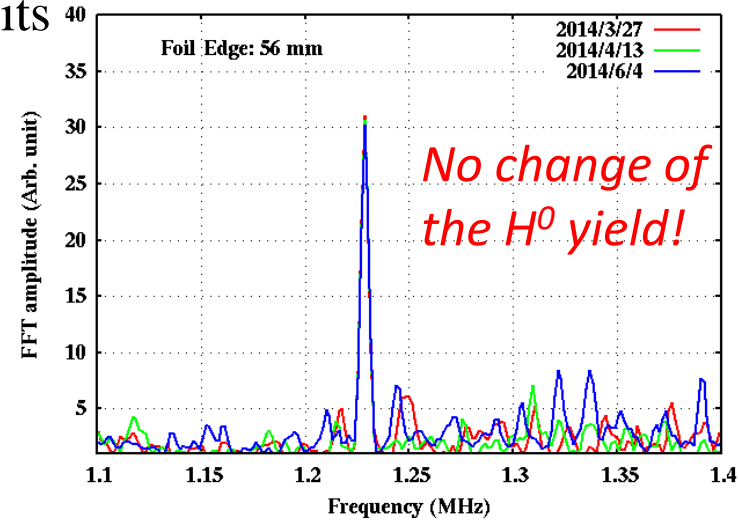
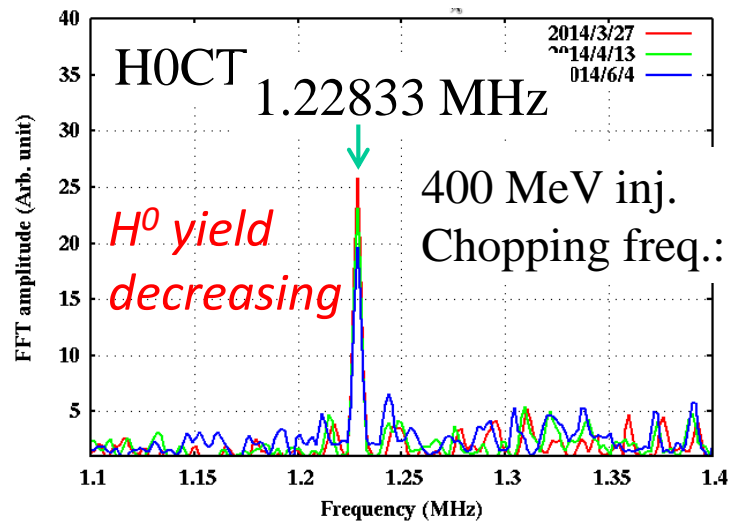
# 400 MeV foil degradation

Starting from March 2014

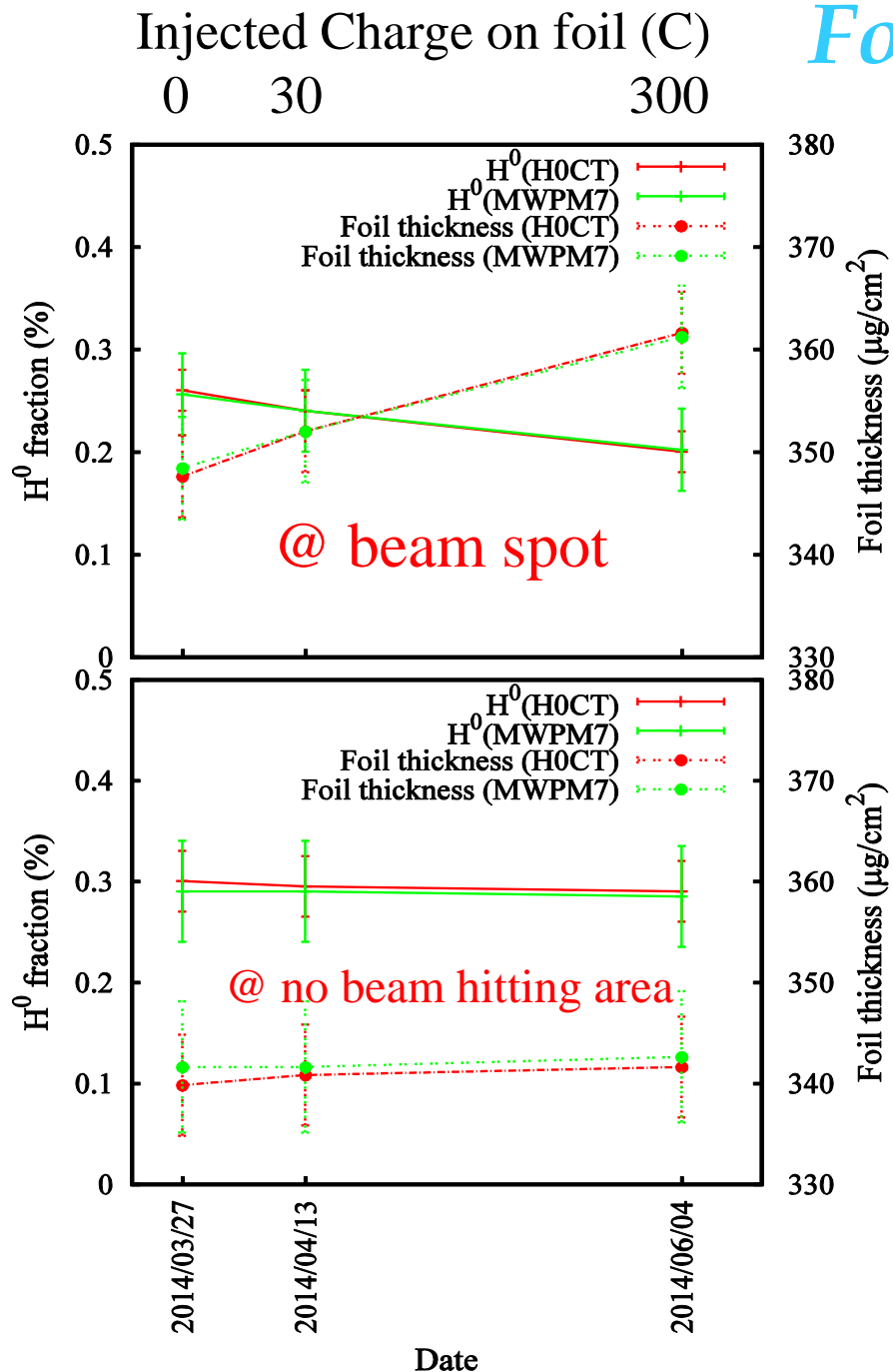
Measured also  
where no beam hits



56mm



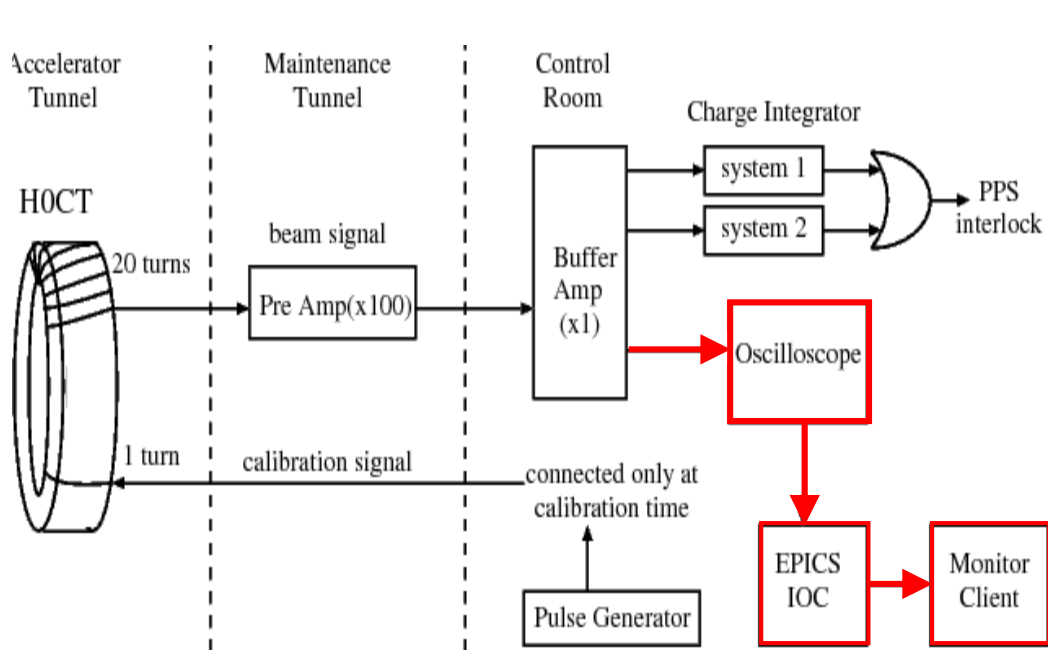
# Foil thickening @ 400 MeV



Starting with a new foil, similar foil degradation (thickening) has also been observed at 400 MeV injection.

Data analysis is in progress and data taking will resumed from Oct. 2014.

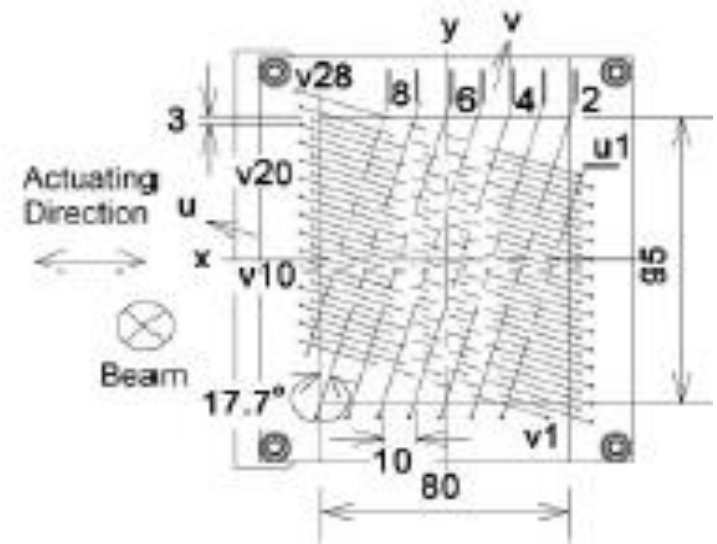
# Configurations of H0CT and MWPM7



## H0CT and data taking logic:

(Used as a PPS interlock system through upper part logic at present).

*For foil studies and online monitoring of the waste beam, we fed buffered signal to an oscilloscope and is controlled by an OPI.*



## MWPM7 configuration:

U plane: 15 wires (pitch 20 mm)

V plane: 48 (pitch 4 mm )

Scan direction: X

For profile:

100 shots @ 1 Hz

Scan  $\Delta x = 0.2 \text{ mm/s}$