大強度ウランビーム生成用
プラズマストリッパーの開発計画

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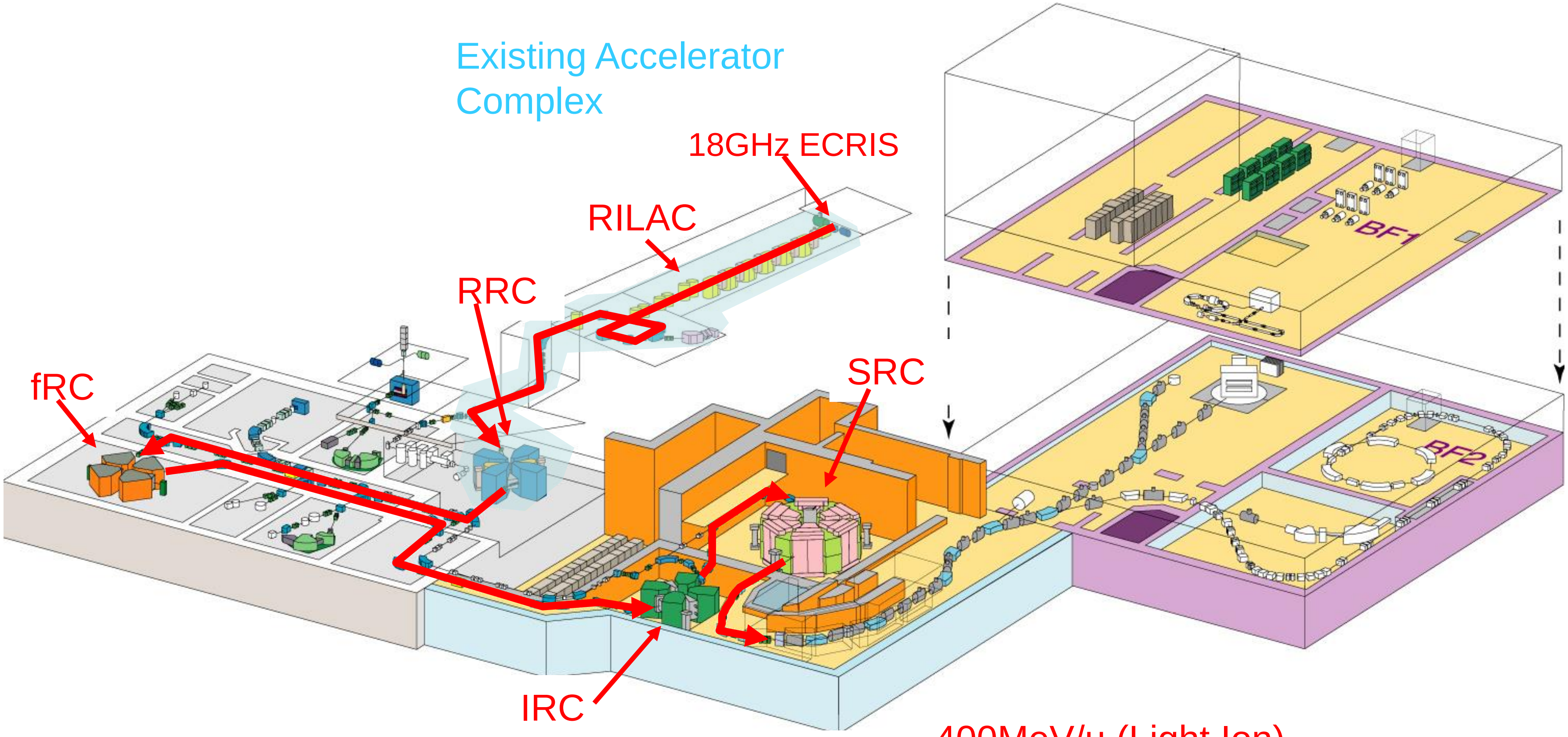
- RIBFの紹介
- RIBF加速器複合系
- 荷電変換装置の開発
- プラズマストリッパーの開発計画

RI Beam Factory (RIBF)

Operation of RIBF (1997~)

The world's most intense RI Beams over the whole range of atomic masses

Powerful Heavy Ion Accelerator (Projectile Fragmentation)



New Cyclotron System

18GHzECR+RILAC+RRC+fRC+IRC+SRC

400MeV/u (Light Ion)
350MeV/u (Very Heavy Ion, Uranium)
I = 1pμA (6 x 10^{12} #/s)

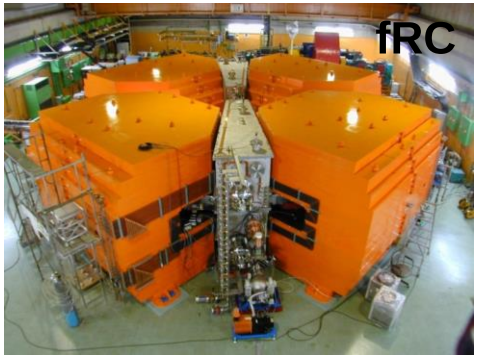
Specifications of RIBF ring cyclotrons

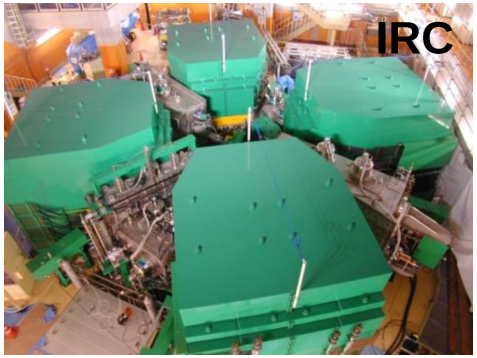
Challenging

	fRC	IRC	SRC	RRC (1986~)
K-number (MeV)	700	980	2600	540
R_{inj} (cm)	156	277	356	89
R_{ext} (cm)	330	415	536	356
Weight (tons)	1300	2900	8300	2400
Sector magnets	4	4	6	4
Number of trim coils (/ main coil)	10	20	4 (SC) 22 (NC)	26
Trim coil currents (A)	200	600	3000 (SC) 1200 (NC)	600
RF resonators	2+FT	2+FT	4+FT	2
Frequency range (MHz)	54.75	18～38	18～38	18～38
Acceleration voltage (MV)*	0.8	1.1	2.0	0.28
Turn separation (cm)*	1.3	1.3	1.8	0.7

*uranium acceleration

SC : superconducting, NC : normal conducting, FT : flattop resonator





Courtesy of N. Fukunishi

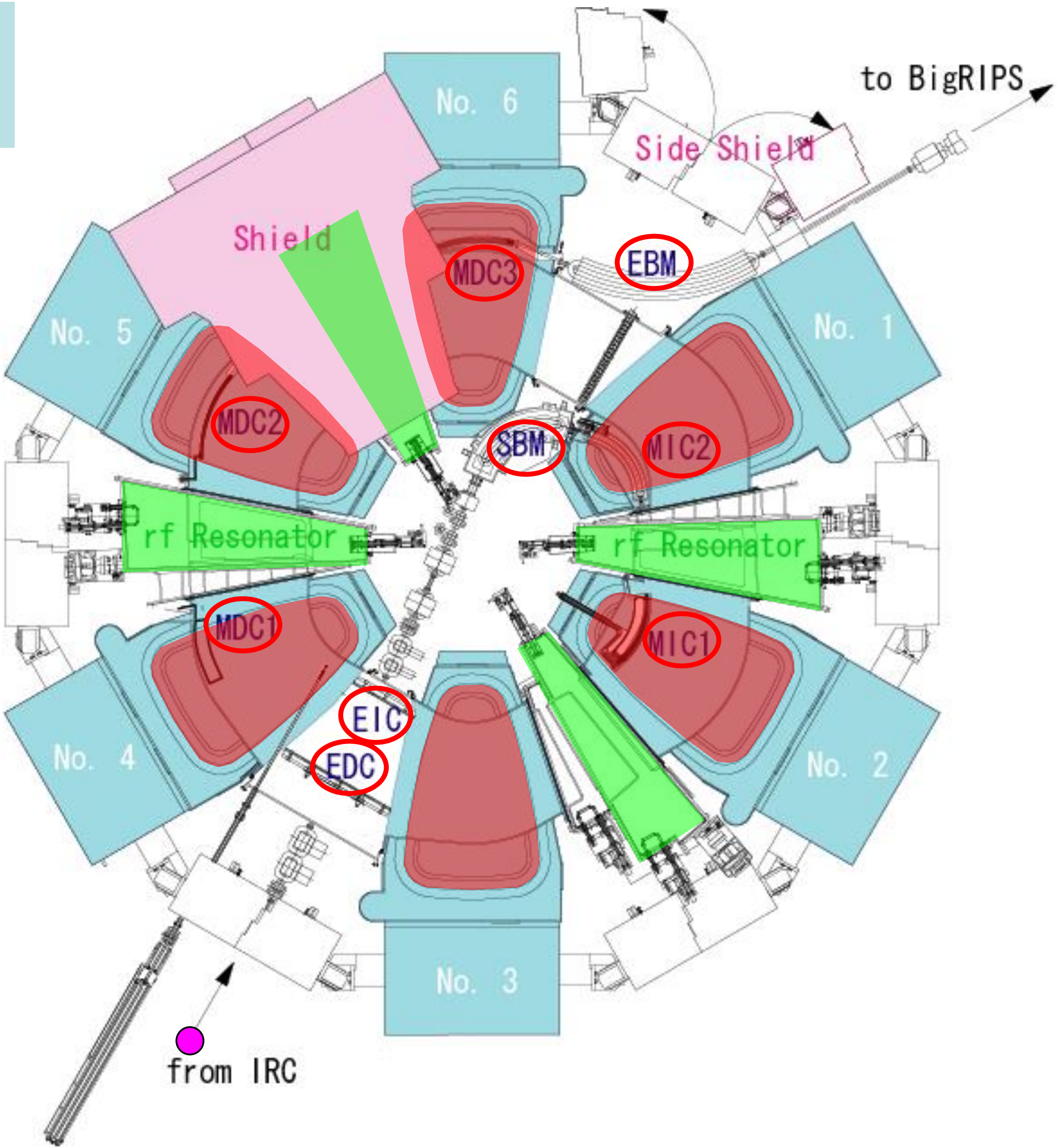
SRC: the World's First Superconducting Ring Cyclotron

K: the maximum bending power of extracted beam from the cyclotron

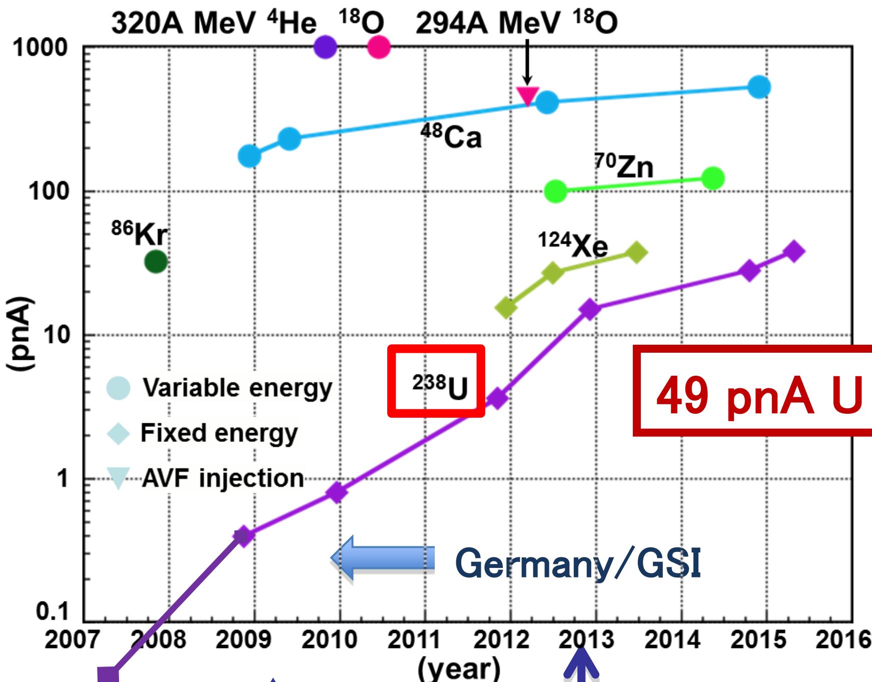
K = 2,600 MeV
Max. Field: 3.8T (235 MJ)
Rf frequency: 18-38 MHz
Weight: 8,300 tons
Diameter: 19m Height: 8m
Total acceleration: 640 MV

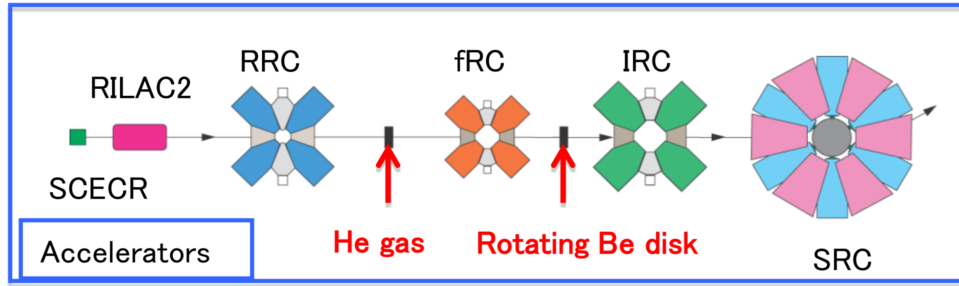
Sector Magnets :6
Rf Resonator :4
Injection elements:
Extraction elements:

Self Magnetic Shield
Self Radiation Shield

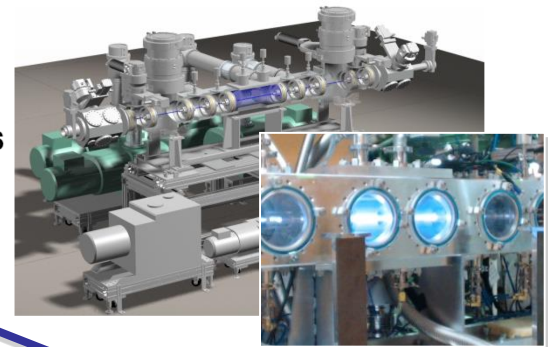


Intensity upgrade at RIBF





49 pnA U (~3x10¹¹#/s 2015)



RIBF starts!

Transmission of the beam: improved
Stability of the devices: improved

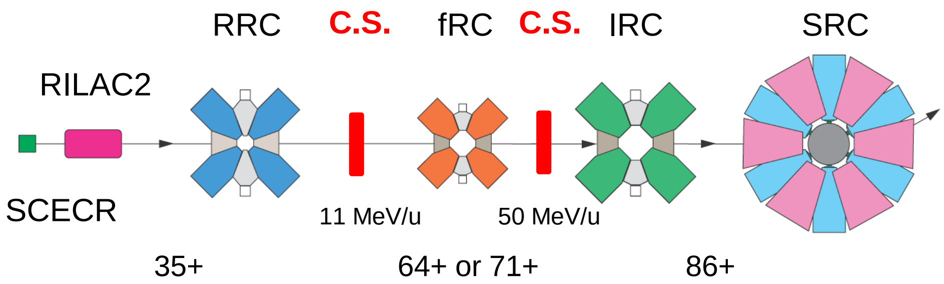
The new injector
(RILAC2) starts!

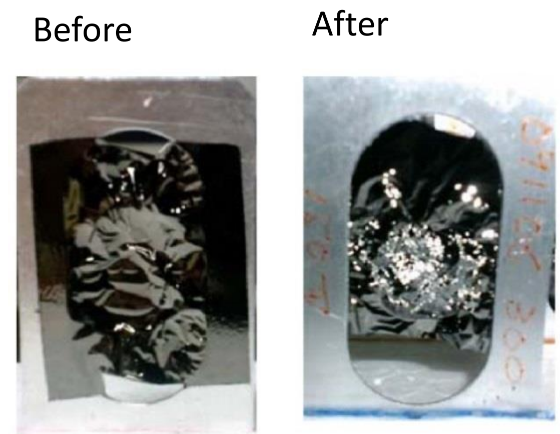
He gas stripper
Rotating Be disk
fRC upgrade
(K570=>K700)

大強度多価イオン生成が可能！

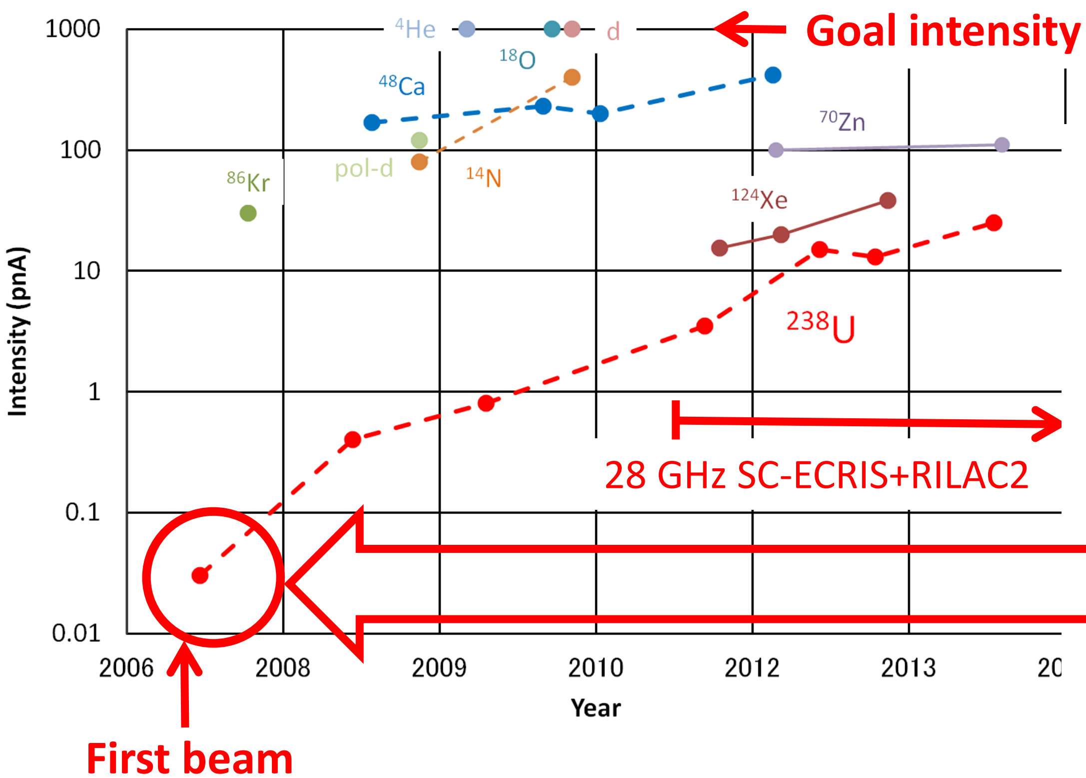
28-GHz SC-ECR

R&D studies on charge strippers (motivation)

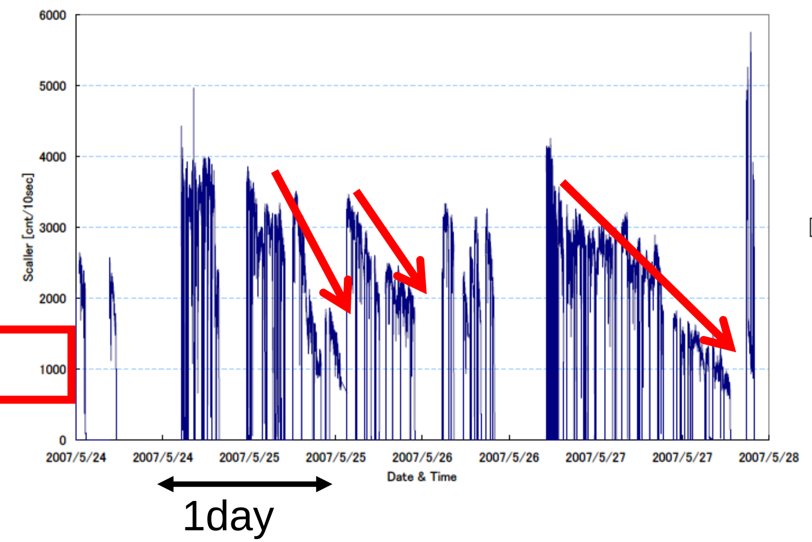




Achieved beam intensity



Current at exit of SRC in 2007



History of R&D on the 1st stripper

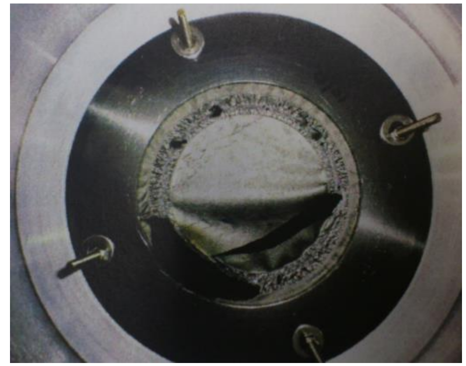
Foil

Rotating cylinder with a large foil

Carbon NanoTube foil

Slow rotation

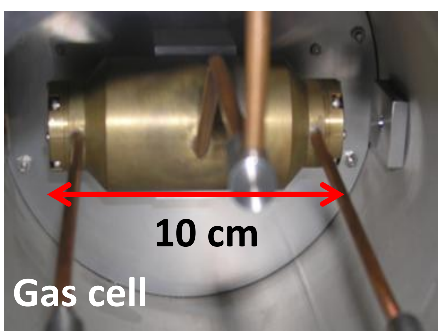
CNT-SDC foils
(User run in 2011)



2008 2009 2010 2011 2012 2013 2014

Gas

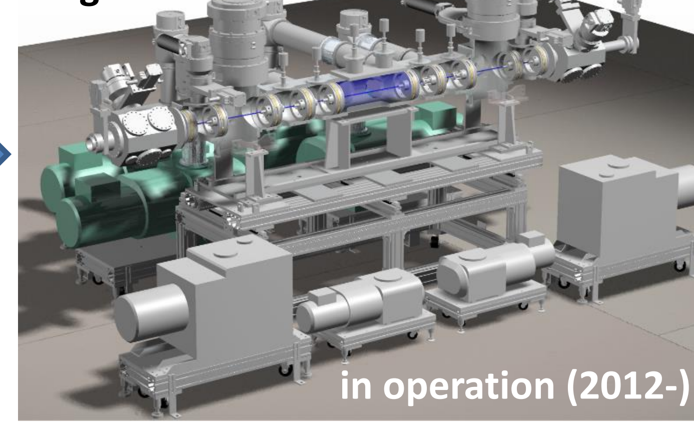
Charge states in N_2, Ar, CO_2
Is lower than acceptable charges.



Cross section of e-loss
and e-cap in Low-Z gas

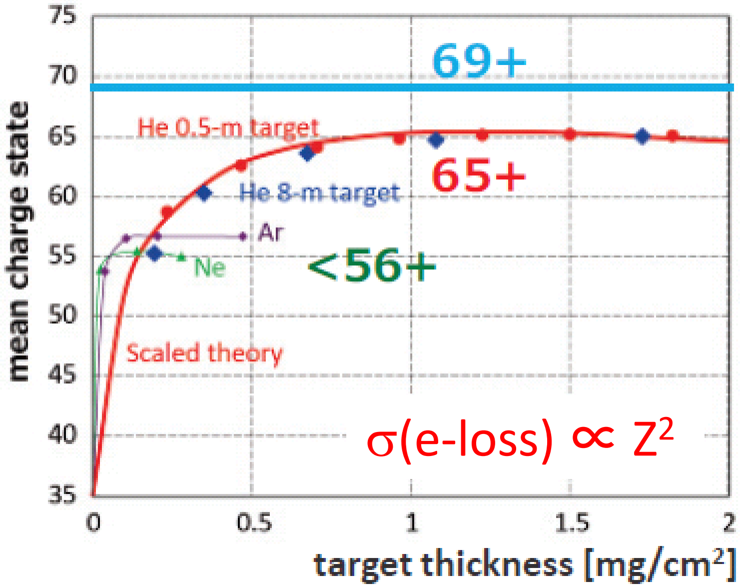
He gas stripper
8 m and 0.5 m prototypes

Technical challenge: Confinement of He gas

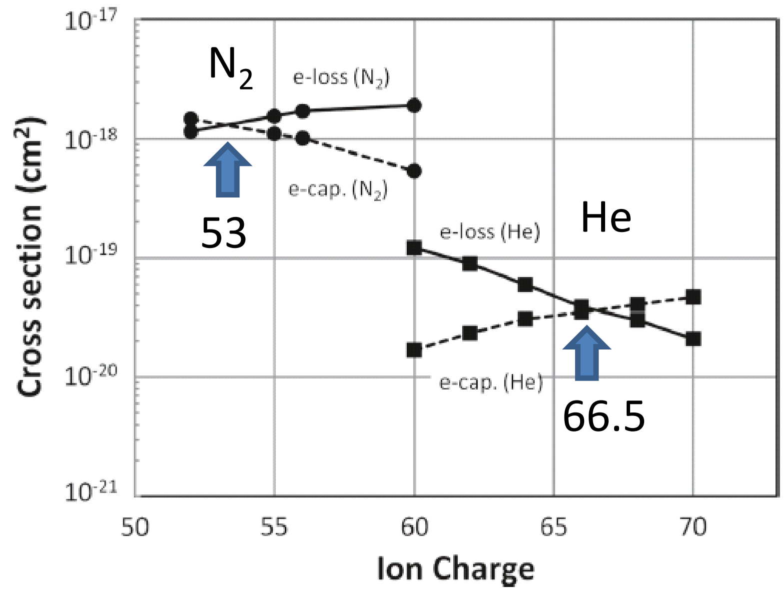


Fundamental data for the 1st charge stripper

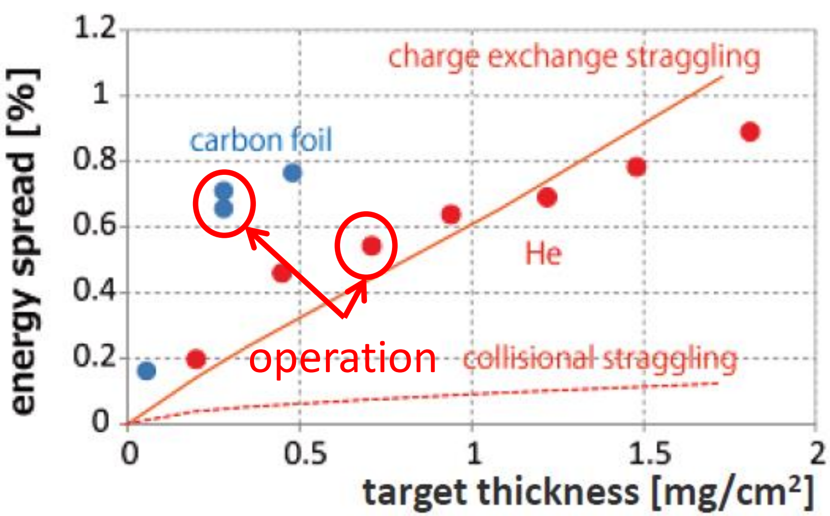
Charge evolution



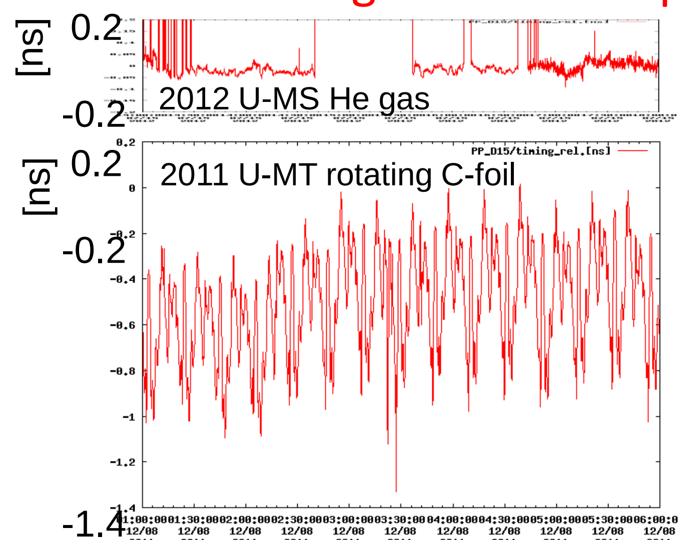
σ(1e-loss) and σ (1e-cap)



Energy spread after charge strippers

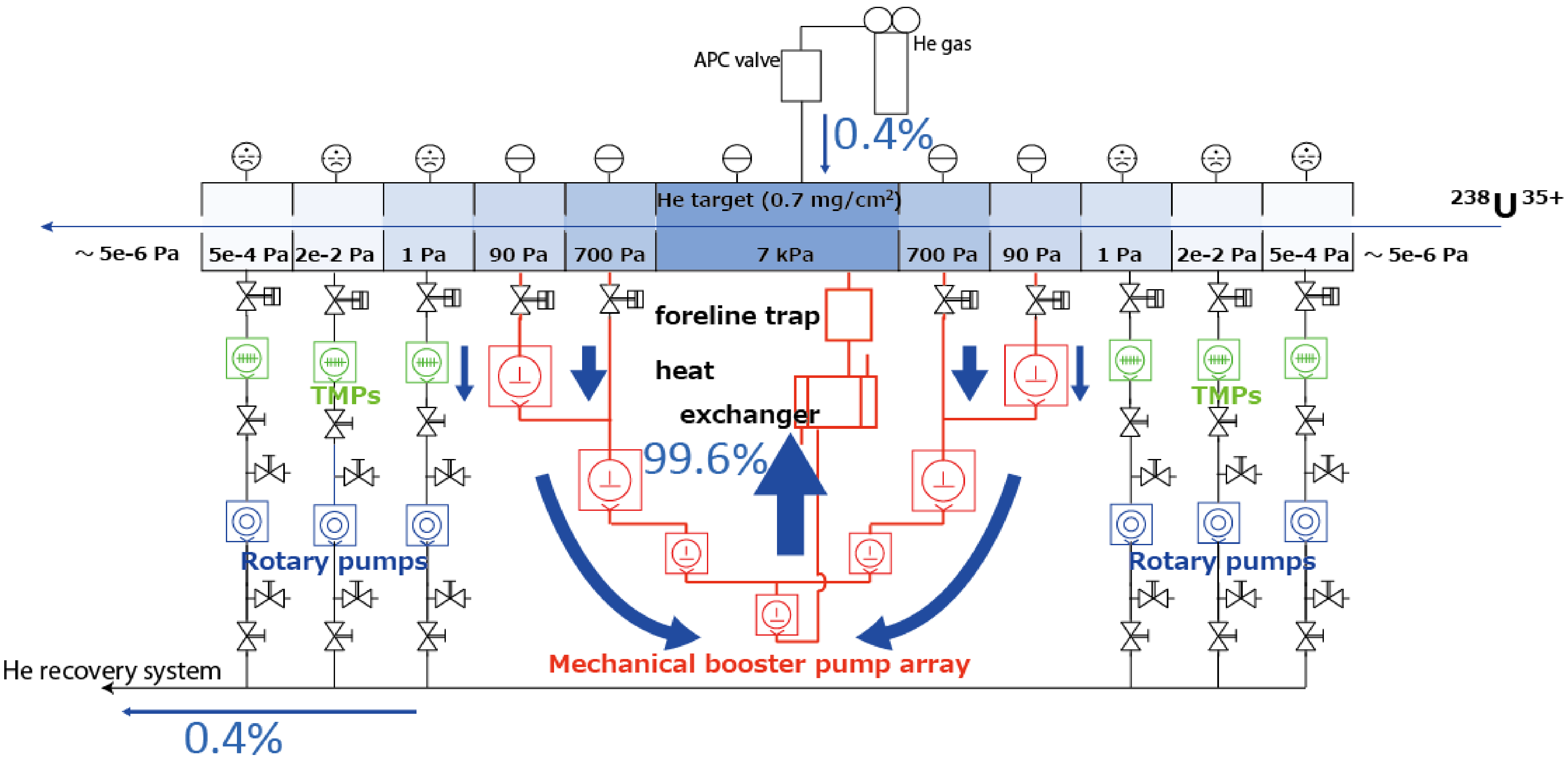


Jitter of beam timing after the stripper



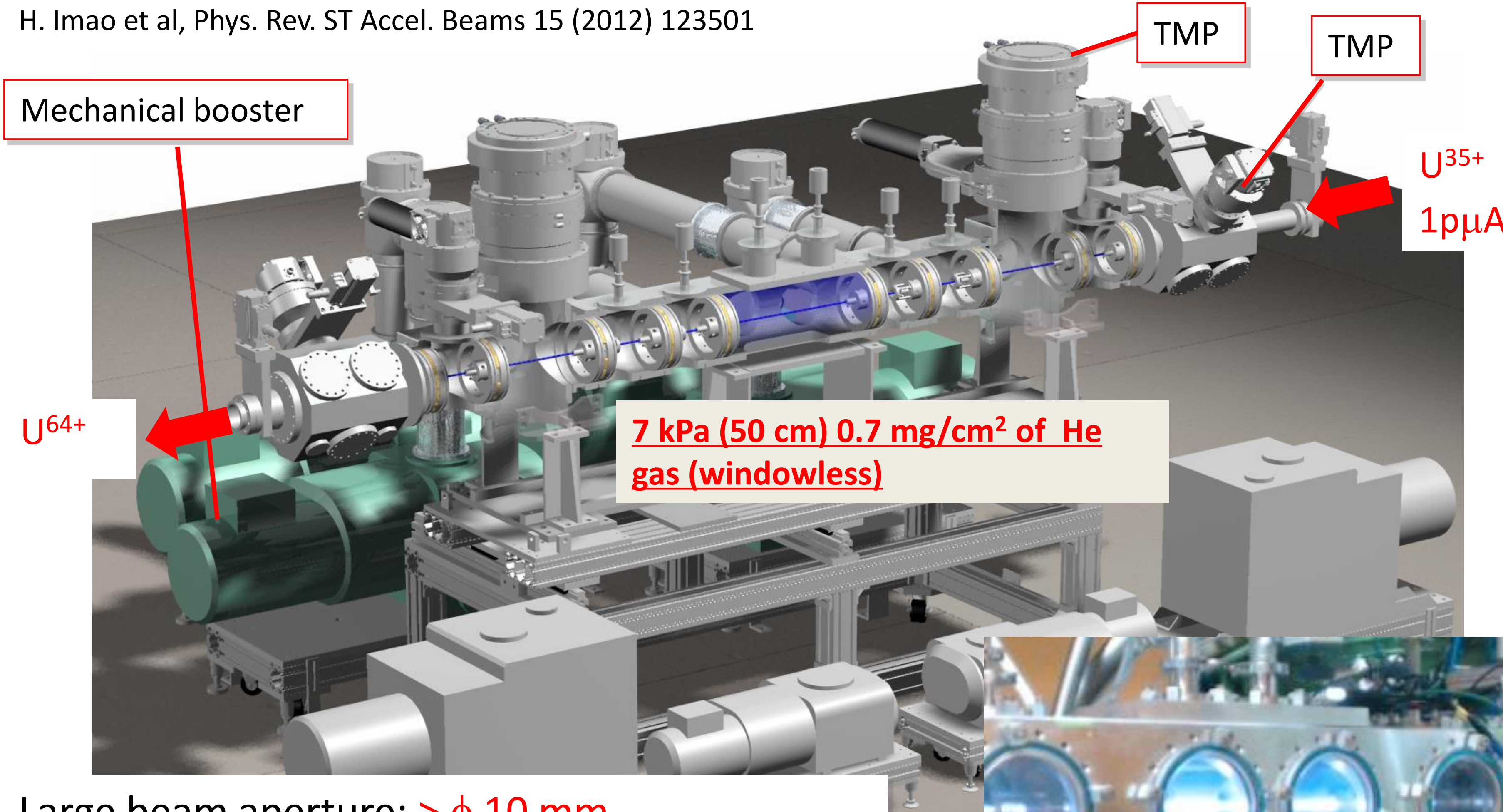
Windowless He accumulation system

- 7 kPa (0.7 mg/cm2) He gas target
- 5stage differential pumping system
- Recirculation by Mechanical booster pump array (oil free)



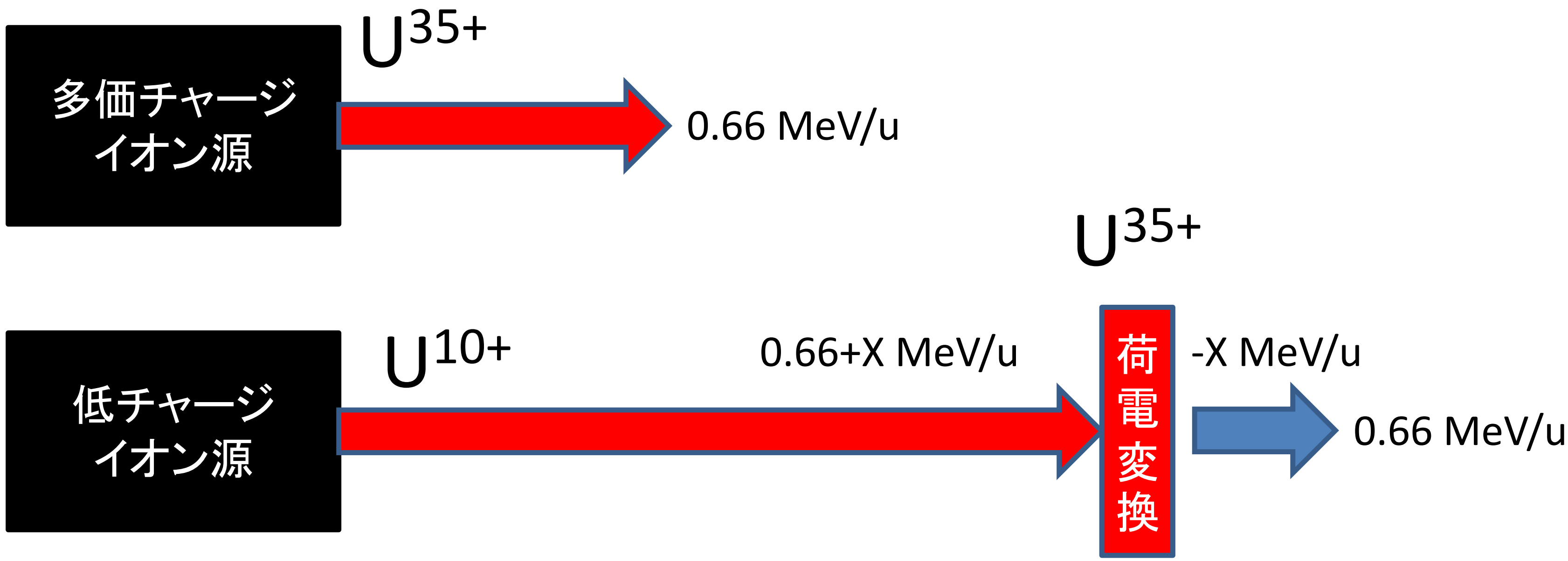
He-gas stripper @ 11 MeV/u (1st stripper)

H. Imao et al, Phys. Rev. ST Accel. Beams 15 (2012) 123501



Large beam aperture: > ϕ 10 mm
8 order pressure reduction: 7,000 Pa => 10^{-5} Pa
5 stage differential pumping: 21 pumps
He circulating volume: 300 m^3/day
(unique recycling system)

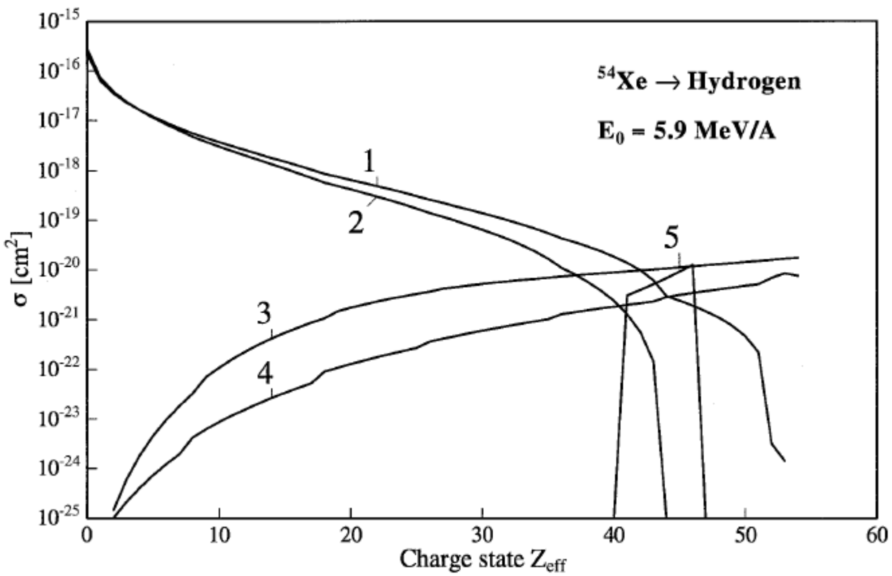
どちらが大強度を出せるか？



収量、ブライトネス、加速コスト

ストリッパーの形態
固体はまず無理
水素(He)ガス
水素(He)プラズマ
（ガスよりも価数が高い）

プラズマストリッパーは低エネルギーほど有利



1 Collisional ionization by ions
2 Coulomb collision with free electrons
3 bound electron capture
4 radiative electron capture = sigma(3) x 1/100
5 Dielectronic recombination

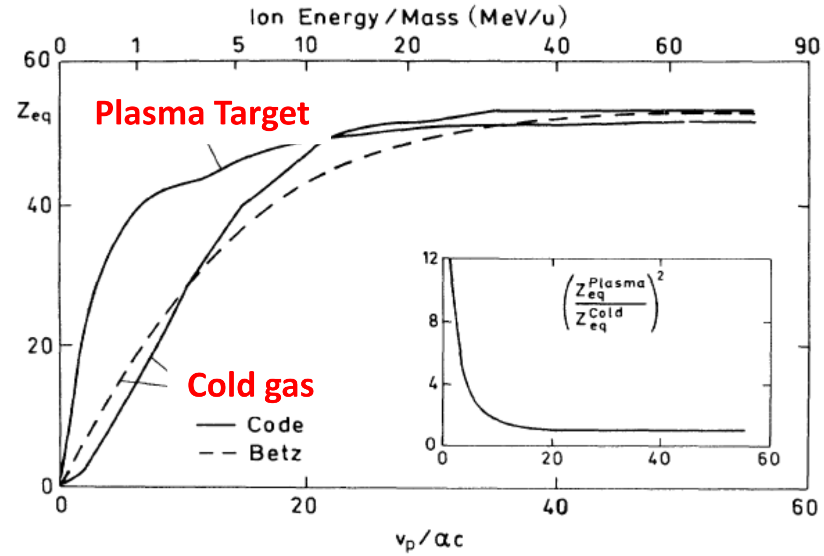
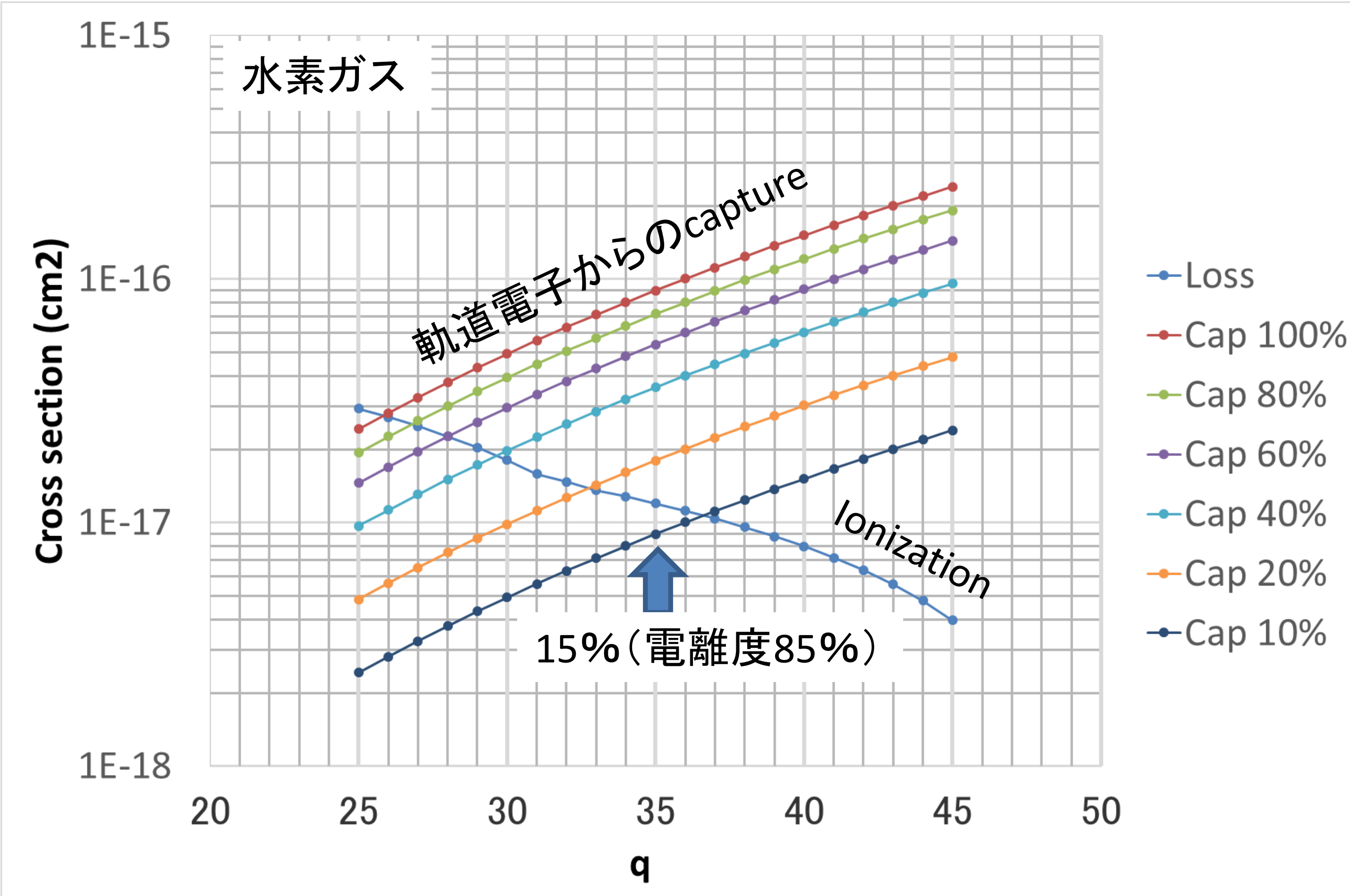


FIG. 4. Equilibrium charge state Z_{eq} for I→H. The target is either 10-eV hydrogen plasma with $n_e = 10^{17}$ cm^{-3} or cold hydrogen gas of the same density; dielectronic recombination is not considered.

U(1.4 MeV/u)+水素で得られる価数



σ(軌道電子からのcapture)>>σ(自由電子からのcapture)

断面積の中性ガスでのデータを取得する予定

電離度（SAHAの式）

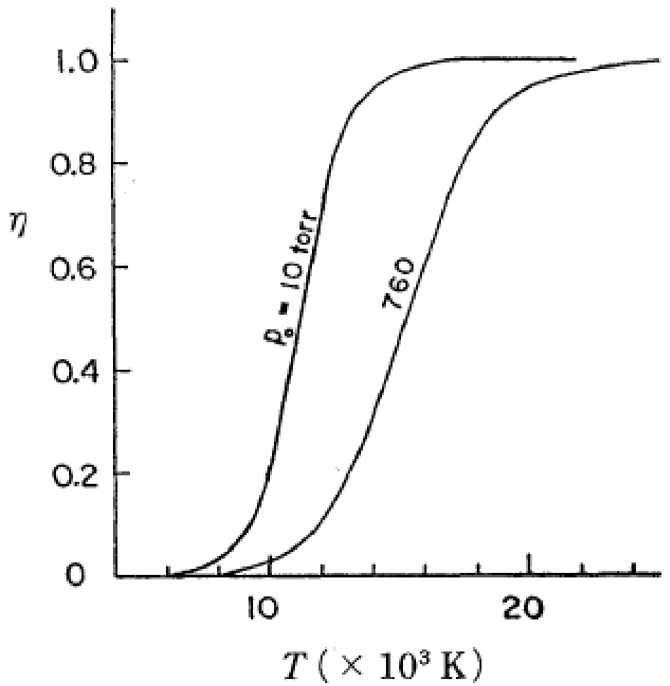
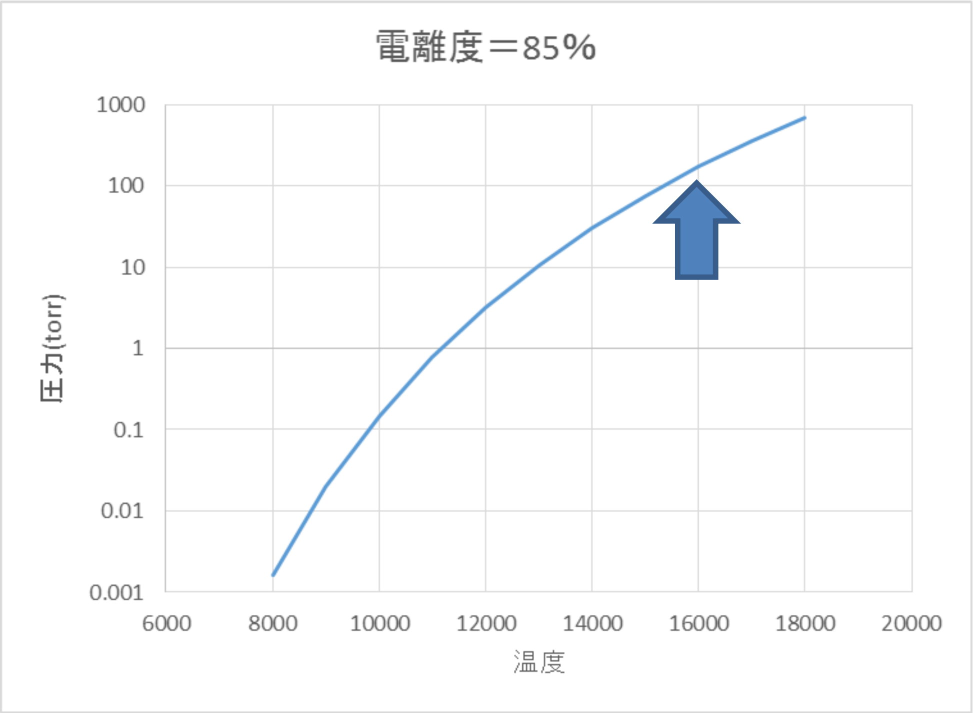


図 2．4　高温水素の電離度（サハの式による）



$$\frac{\eta^2}{1-\eta^2} = 2.5 \times 10^{-4} \frac{T^{5/2}\,(\mathrm{K})}{p_0\,(\mathrm{torr})} \times \exp\left(-\frac{1.57 \times 10^5}{T\,(\mathrm{K})}\right) \qquad (2.10)$$

電離度85%を得るためには、
例：T=16000K, p0=170 torr

必要な厚み(20ug/cm2と仮にして）

- ガス：水素
- T=16000K, P=170 torr, 長さ：50cm
- Thickness=17ug/cm2
- プラズマの密度：10^17/cc

アークプラズマのスタディのきっかけ

Difficulty in accumulation of low-Z gas

The existing gas stripper：He ～15 μg/cm^2 (0.7 kPa)

(cf. N_2 1.3 mg/cm^2)

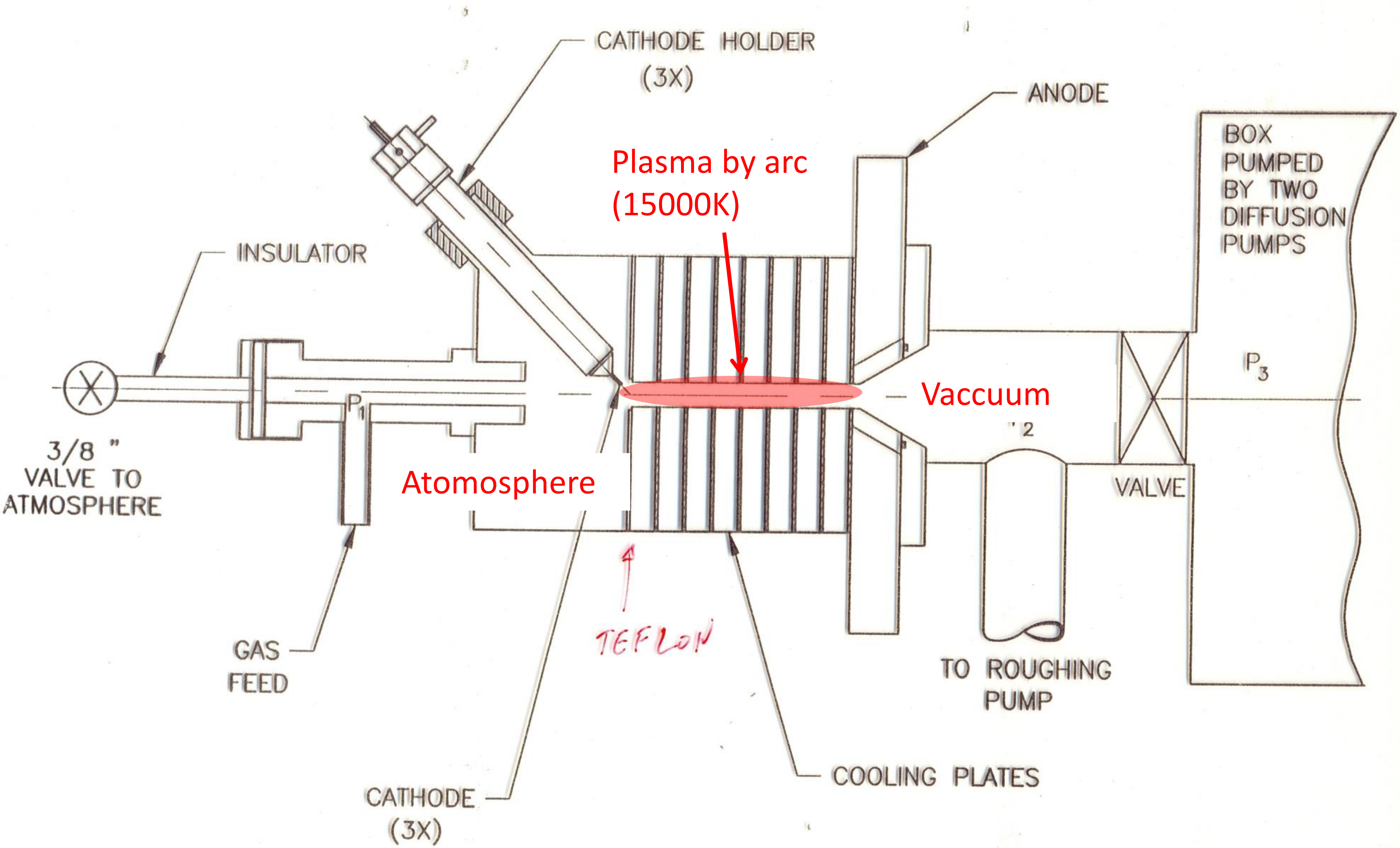
~1mg/cm^2 of low-Z gas is necessary to be accumulated to get higher charge state.

→ *A new device to make it possible …*

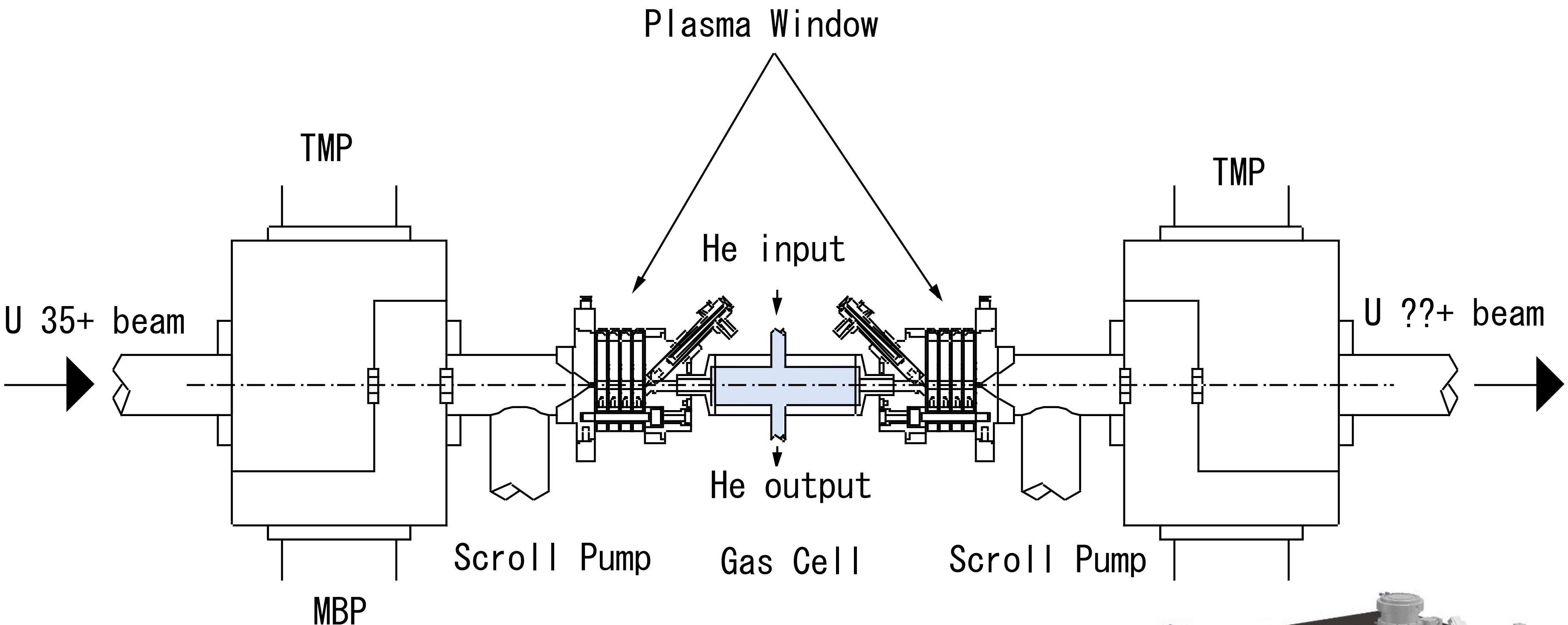
Plasma Window (1995-)

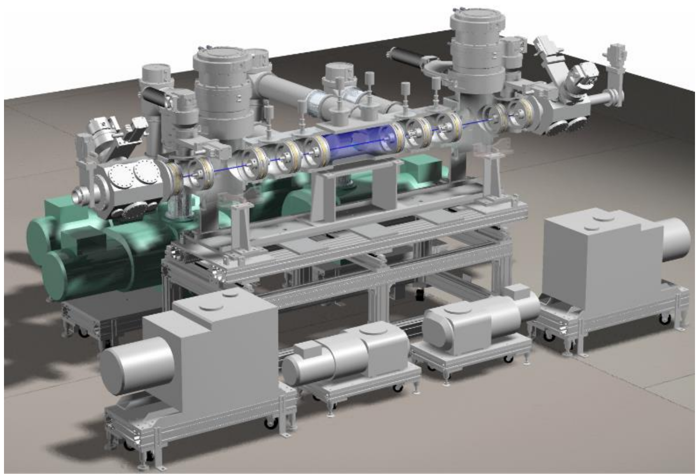
Inventor：Ady Hershcovitch (BNL)

Plasma Window (Wall Stabilization Theory)



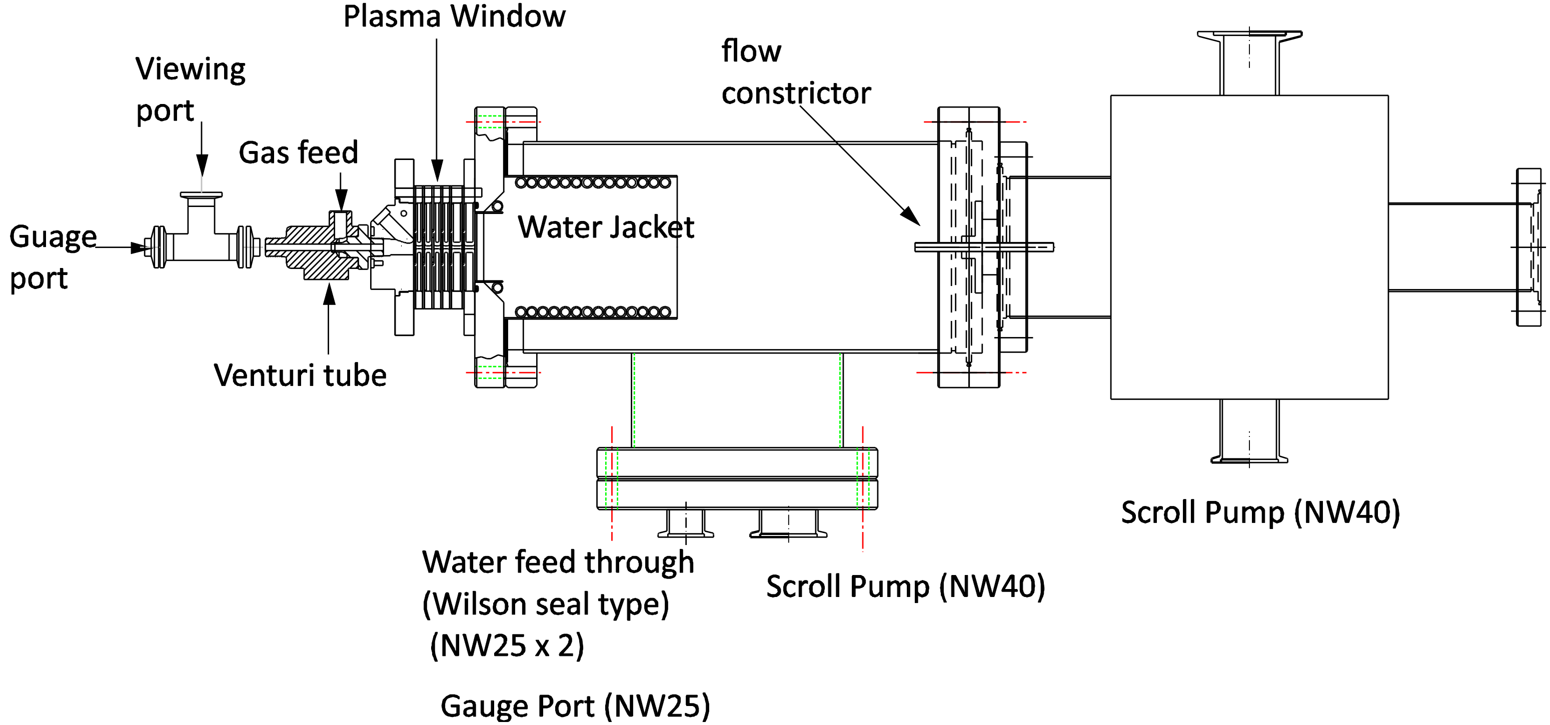
Schematic sketch of the low-Z gas stripper using two plasma windows





実際は、通常の差動排気を用いた

R&D on Plasma Window at RIBF (-March 2011: Kuboki)

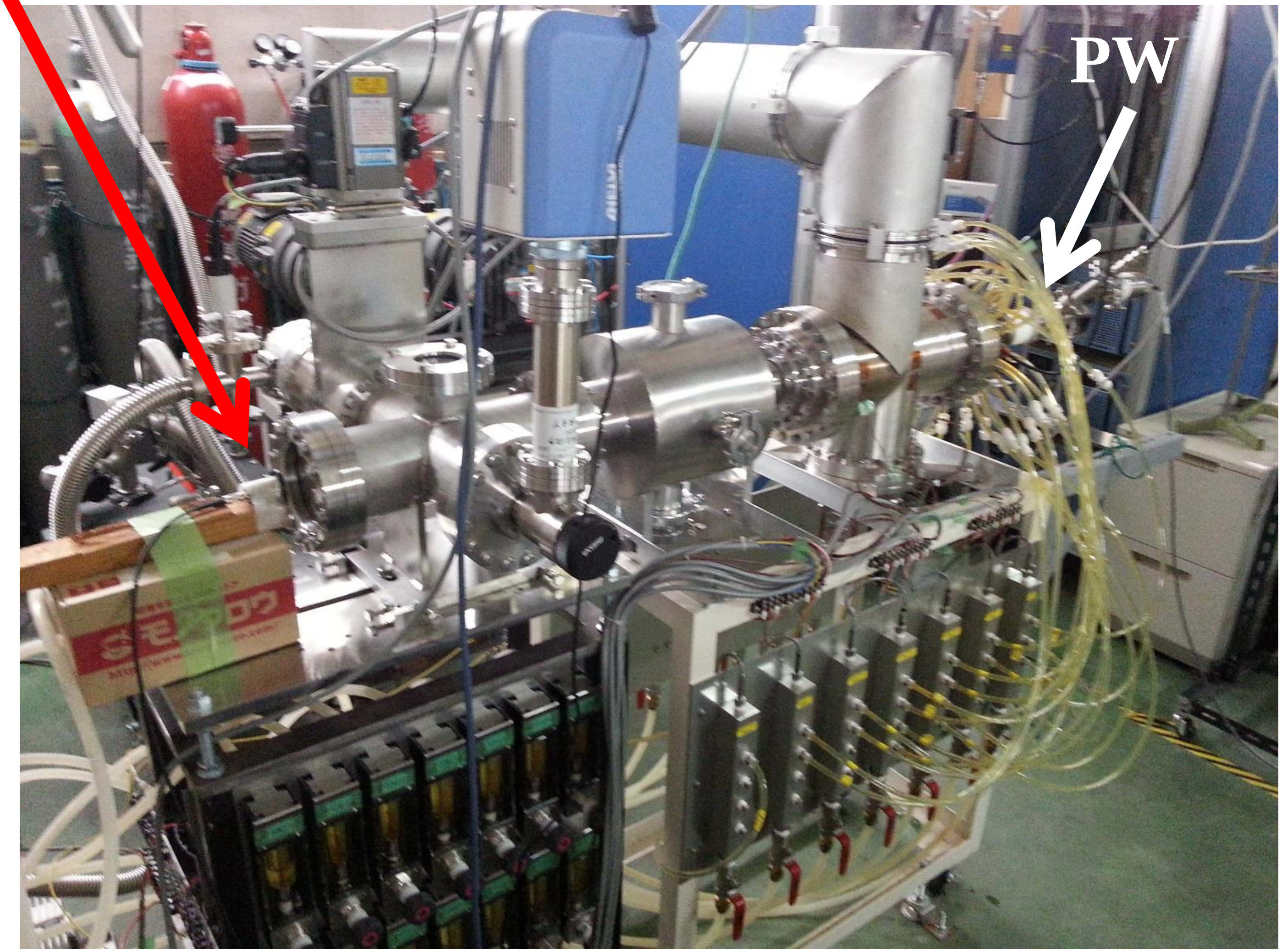


Results: Ar → He, d = 2 mm → 6 mm (~2013)
gas cell with one plasma window

Restart: toward Larger aperture of 1~2cm (Sep. 2015, Ikoma)
Spectroscopy of arc plasma (with help from Prof. Namba)

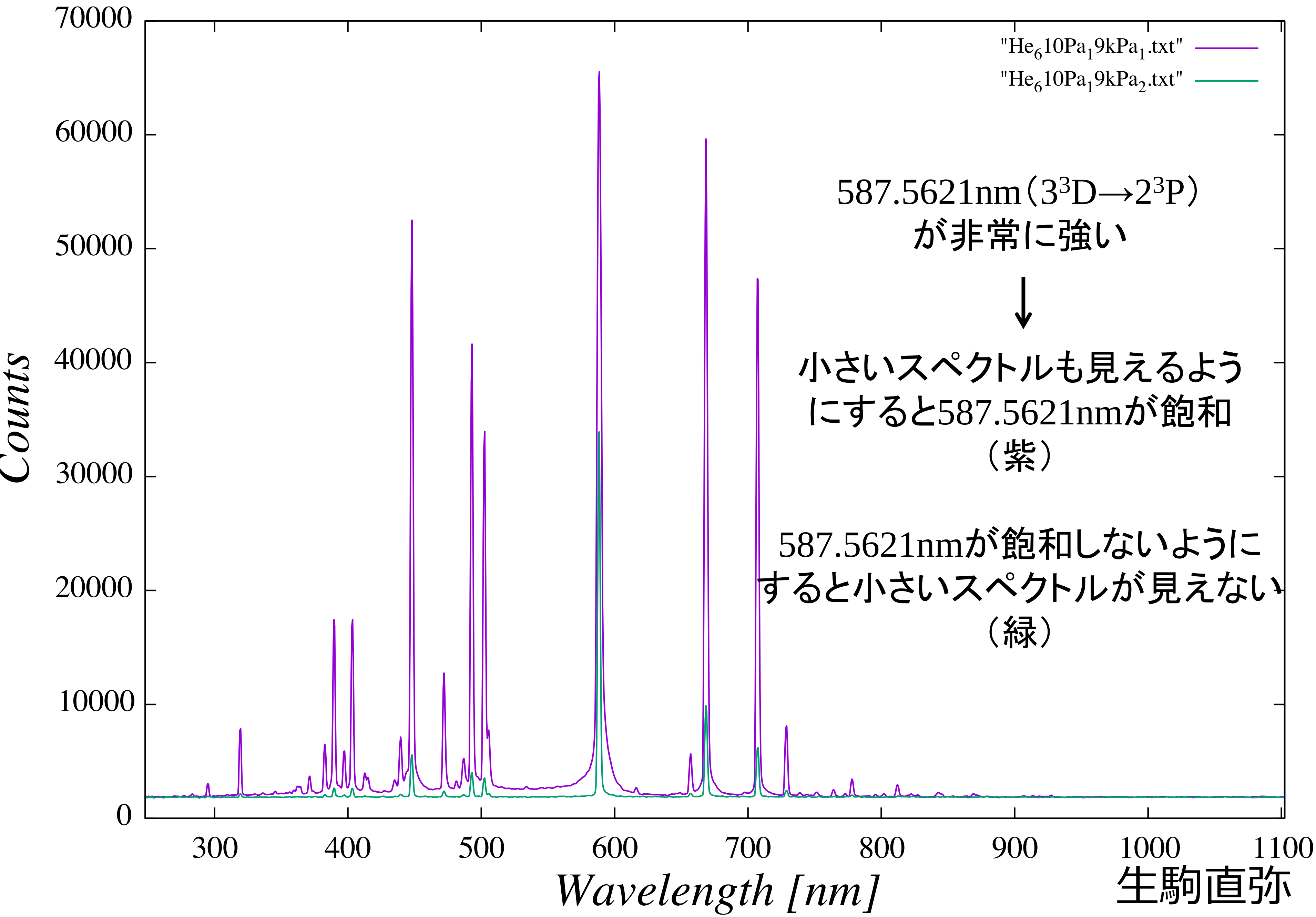
実験セットアップ

コリメータ



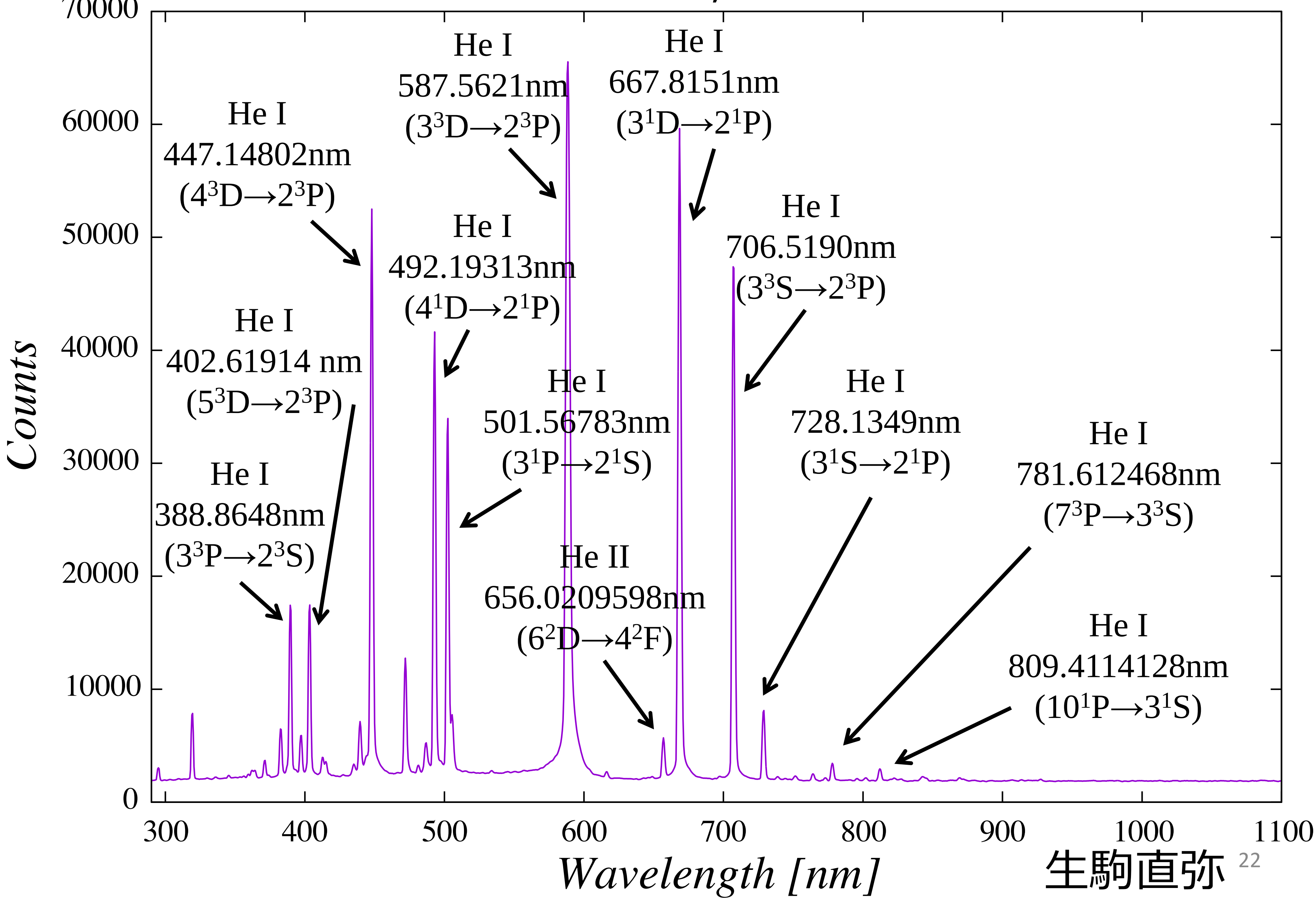
生駒直弥

He（5枚，真空側から）



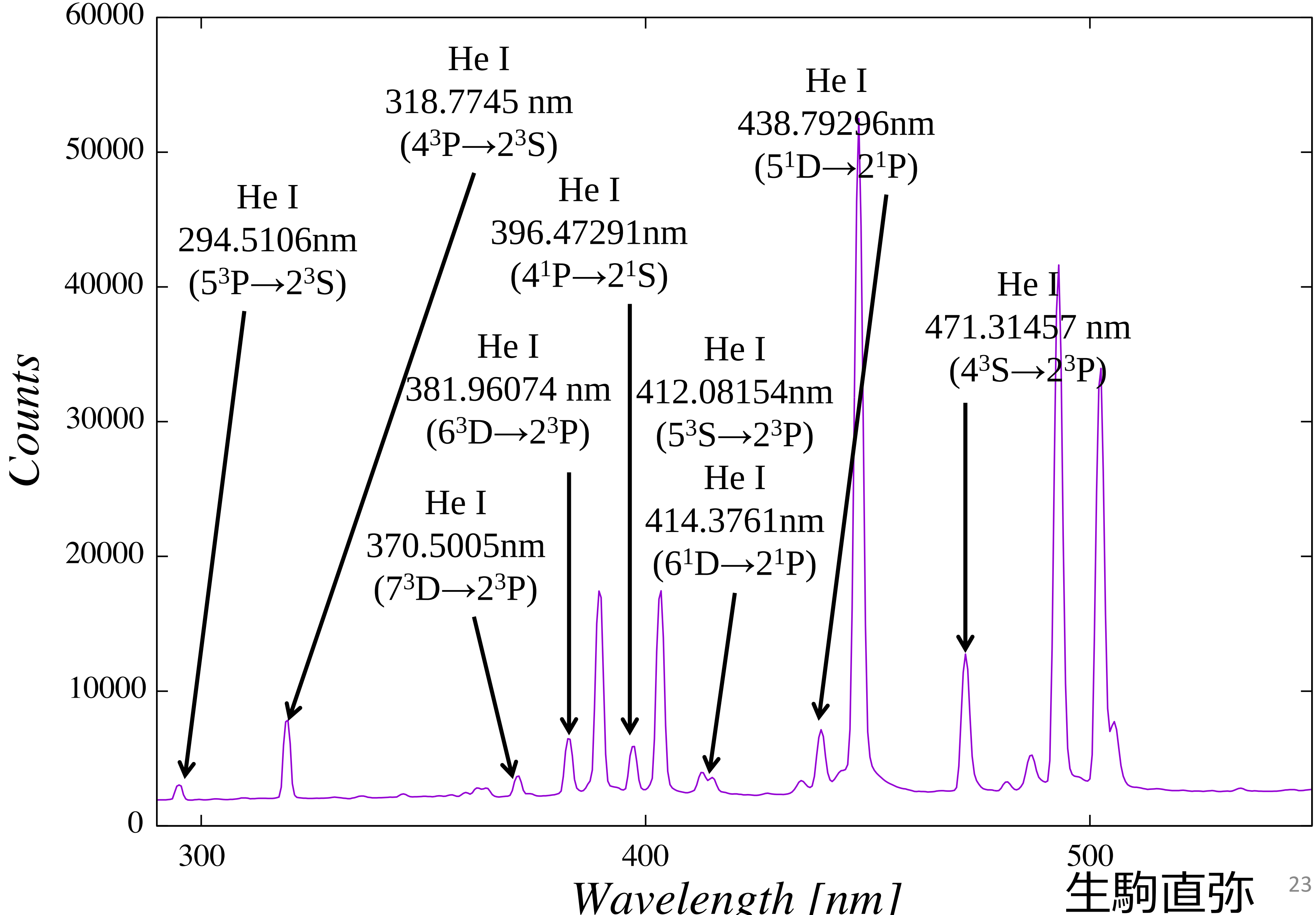
生駒直弥

スペクトルのアサイン（その1）
※小さいスペクトルも見えるよう，飽和した方を載せています



生駒直弥

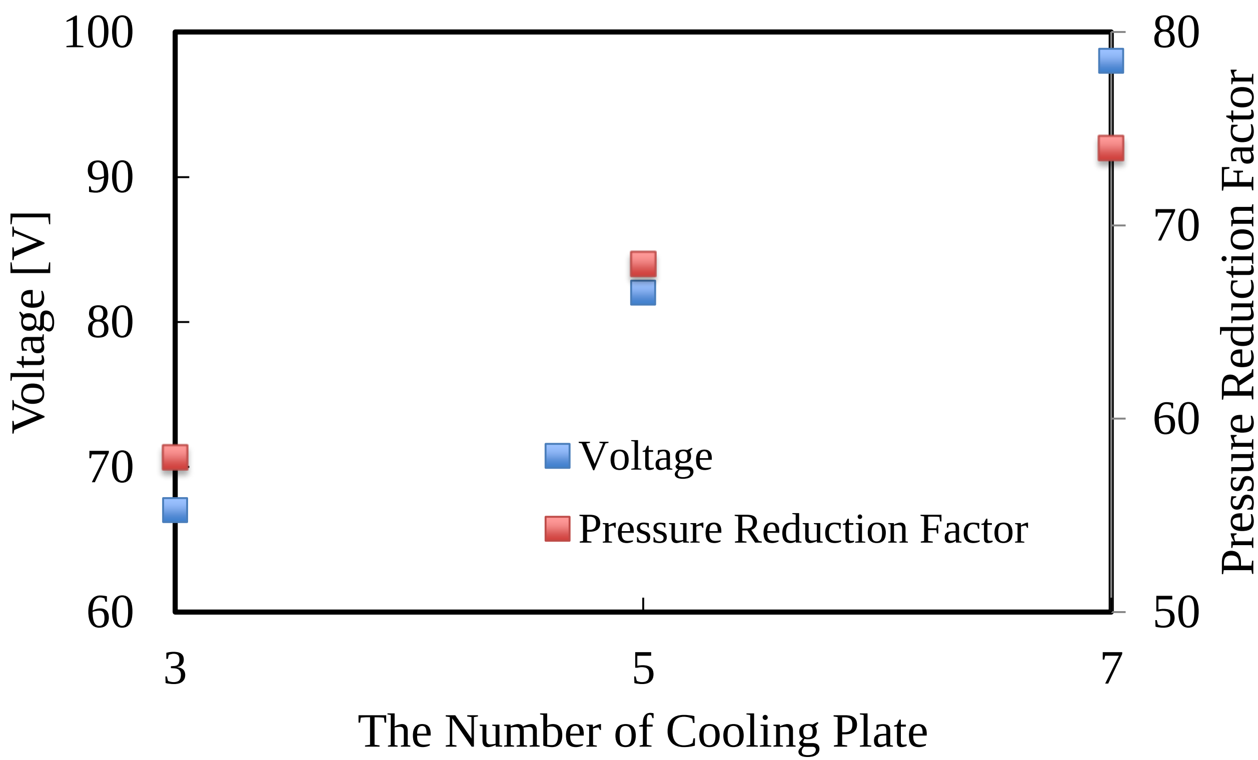
スペクトルのアサイン（その2）
※短波長側，拡大



生駒直弥

PW性能の長さ（中間電極枚数）依存性

電流は36A/Cathode，流量は17.1slm固定



中間電極枚数に比例し，電圧，圧力比が増加

生駒直弥

まとめ

- RIBF加速器は、2007年から、順調にウランイオンビームのビーム強度を増やしている。
- 多価イオン源のビームを増加させると、エミッタンスも増加し、ブライトネスが増えず、結果的に最後の加速器まで通らず、ネットに考えてビームが増えない可能性が出てきた。
- 低チャージから始めて、ある程度加速してから価数が高く取れるプラズマストリッパーでは電子を剥ぎ取る方法を検討を開始
- 計算：
  - プラズマ温度=16000K
  - P=170 torr,
  - 50cm程度のものが必要
  - Thickness=17ug/cm2
  - プラズマの密度：10^17/cc
- 予定
  - **水素での点火（難しい？）**
  - **中性ガスの断面積をしっかり測定**
  - **分光等により電子温度や電子密度等を測定**
  - **プラズマウィンドウの長さ依存性**