Intense Beam Operation of the MSU/NSCL Cyclotrons*

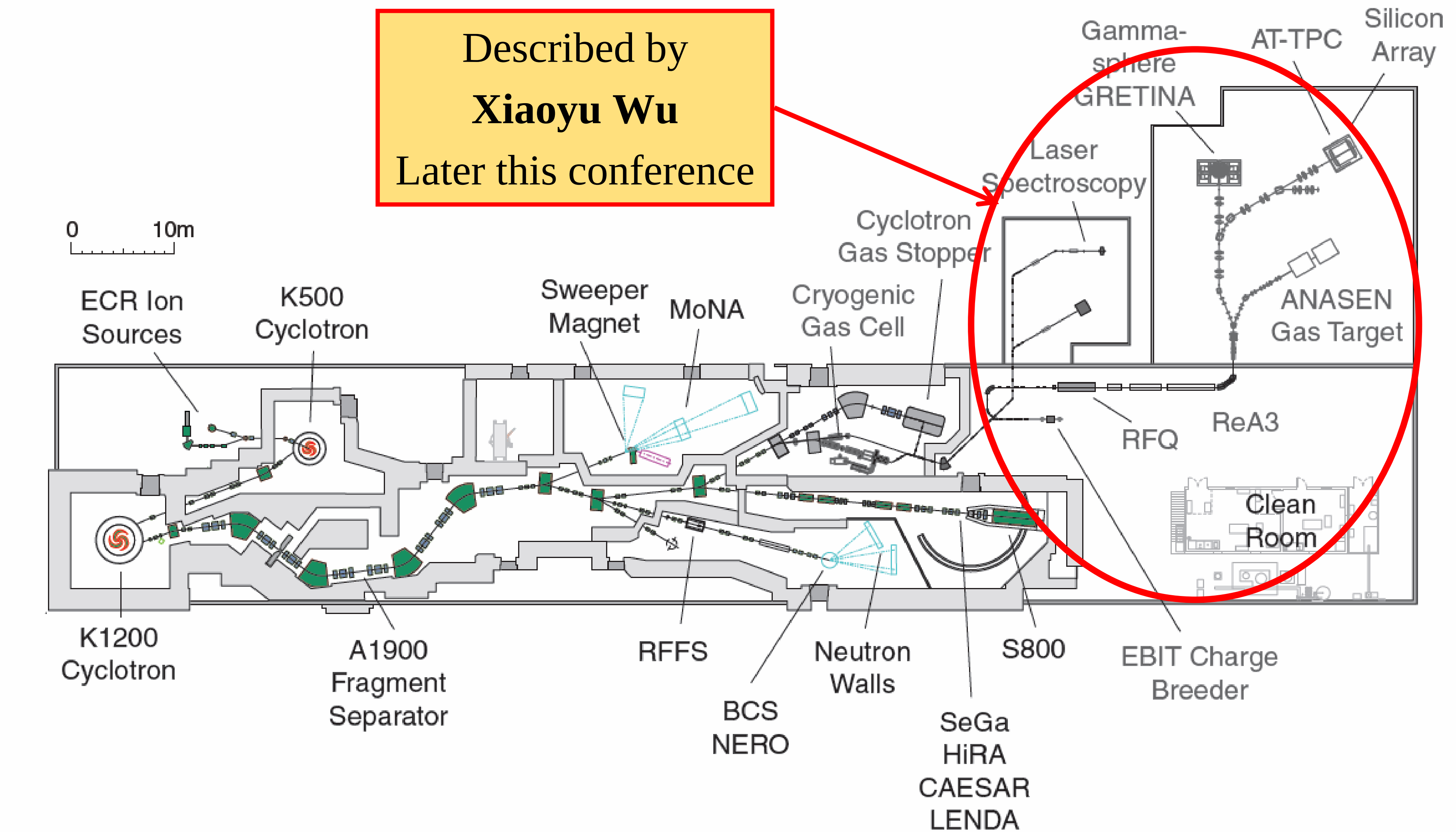
J. Stetson, G. Machicoane, F. Marti, D. Poe, NSCL/MSU

* *Work supported under NSF Grant PHY0606007*

Presenter: stetson@nscl.msu.edu

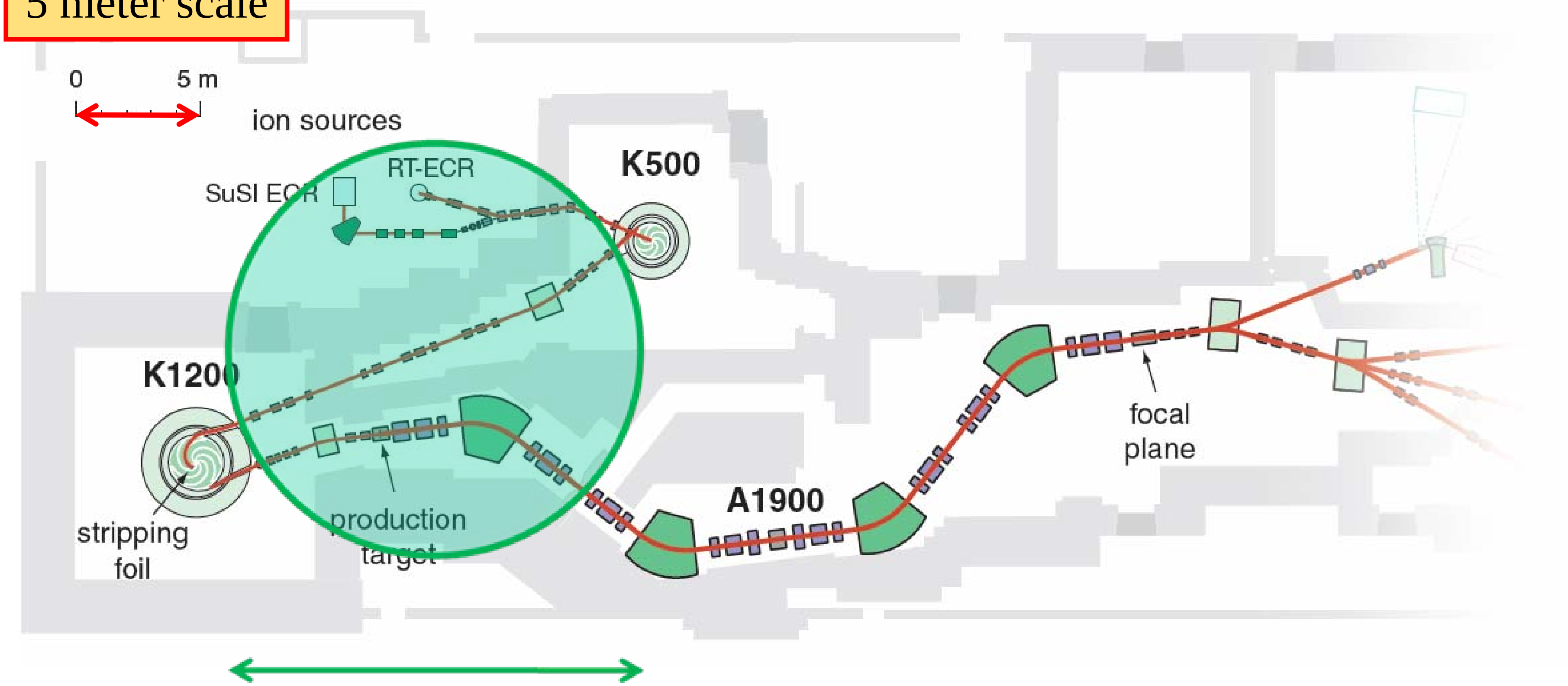
Cyclotrons+A1900+Experimental Areas

Described by
Xiaoyu Wu
Later this conference



Cyclotrons + A1900

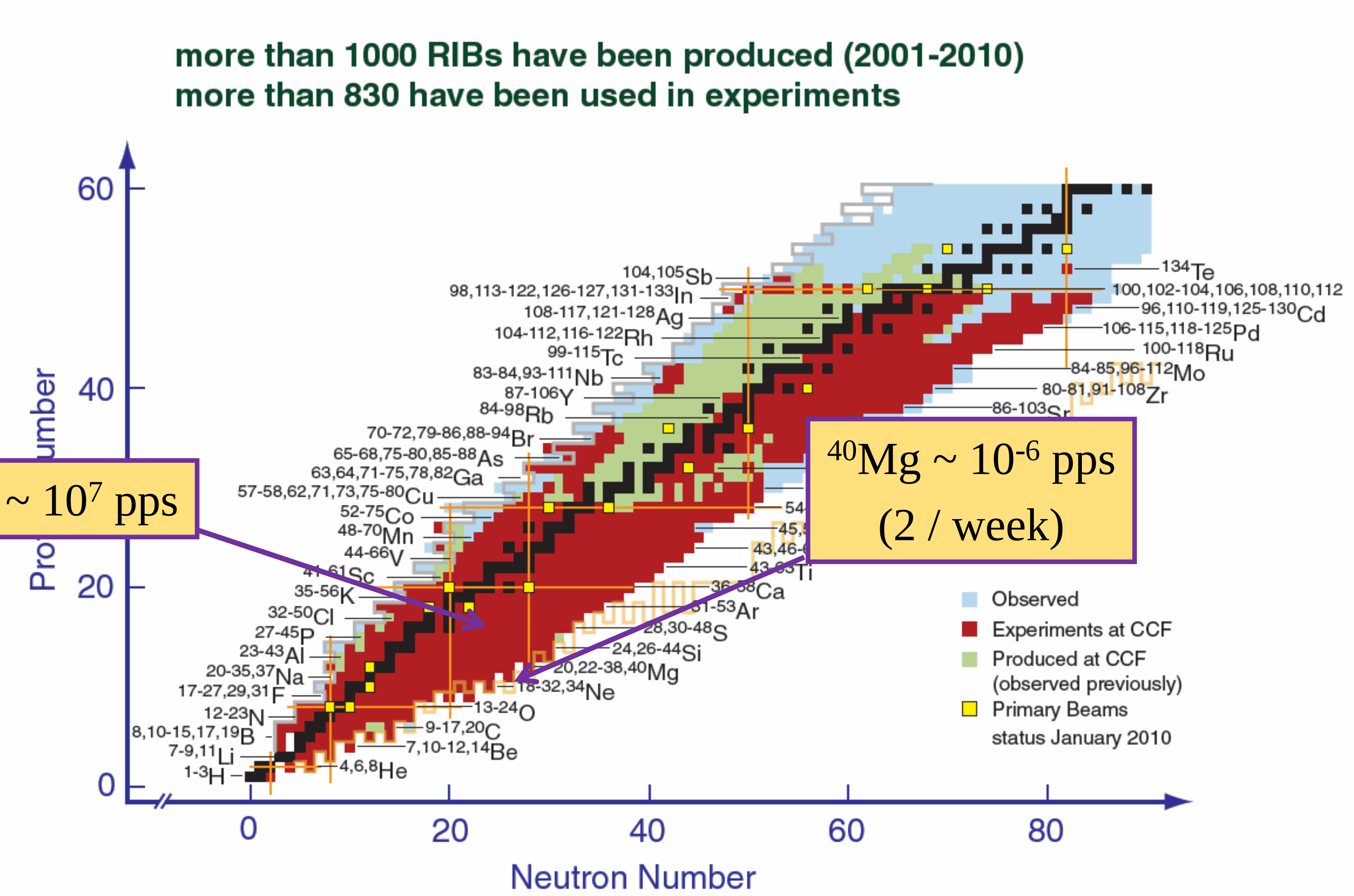
5 meter scale



RIKEN SRC Scale!


Present
Beam Status

Our “Real” Beam List ~ 1000 Entries



^{46}Ar ~ 10^7 pps

^{40}Mg ~ 10^{-6} pps (2 / week)

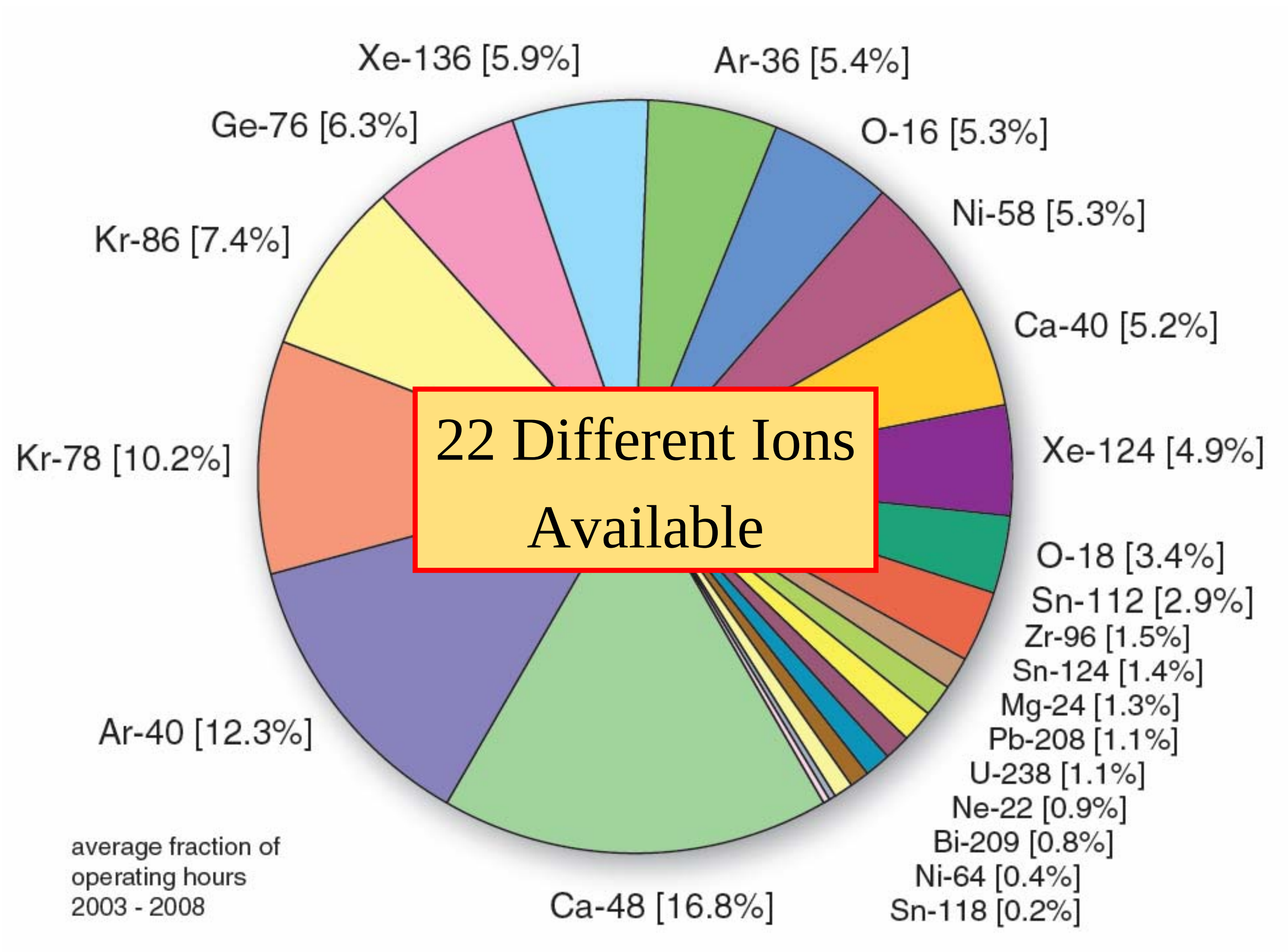
Superconducting Compact Cyclotron Driver(?)

Experimental Demand is Virtually All for Fragment Beams

"Maximum" Primary Beam Power is usually Desired (a task for which these machines were not designed)

Pushing the Limits of what is possible to do with these machines

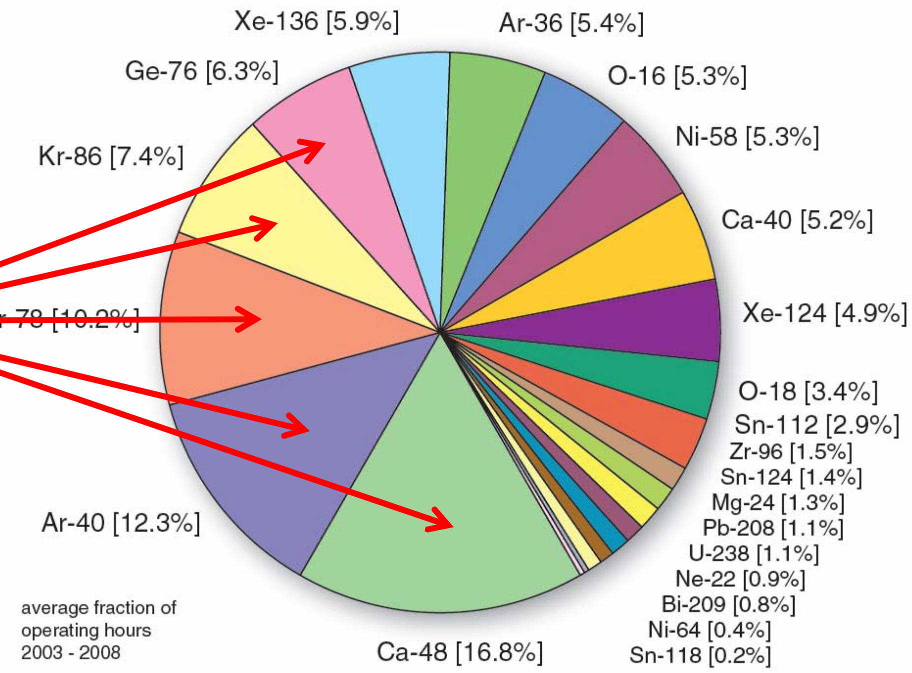
Fraction of Operating Hours by Accelerated Ion Type



Demand Influences Development

5 Beams account for ~ ½ the total running time

The most-requested beams
Generally have
the best performance.
(^{48}Ca, ^{40}Ar, ^{78}Kr, ^{76}Ge, ^{86}Kr,)



4 - 7 Day duration runs → Limited Time for "Perfect Tunes"

Cyclotron Beam Intensities - 2010

1) not Peak values

2) not Guaranteed values

→ *Reasonably* Achievable

On this list:

P(max) = 1200 W

P(max) = 1 W

→ What are the Present Limiting Factors?

Power or Loss-Limited Beams (400 – 1200W)

ION	Energy (MeV/u)	Intensity (pnA)	Power (W)
16-O	150	500	1200
18-O	120	500	1080
22-Ne	150	220	726
24-Mg	170	200	816
36-Ar	150	150	810
40-Ar	140	200	1120
48-Ca	140	140	941
78-Kr	150	100	1170
86-Kr	140	70	843
124-Xe	140	25	434

Danger Zone:
> 1000 W (light)
To
> 300 W (heavy)

Range in Tungsten (Deflector Septum)

ION	Energy (MeV/u)	Range in Tungsten (mm)
16-O	150	4.1
18-O	120	3.2
22-Ne	150	3.6
24-Mg	170	3.4
36-Ar	150	1.8
40-Ar	140	1.8
48-Ca	140	1.8
78-Kr	150	1.0
86-Kr	140	1.0
124-Xe	140	0.7

~ Factor of 6
in
Deposited
Energy Density
per
Watt

Special Cases: Production Target (Be) Damage

ION	Energy (MeV/u)	Intensity (pnA)	Power (W)
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124-Xe	140	25	434

Medium-heavy beams at ~ 1 kW causes damage within the 1 mm dia. impact region

Rotating Wheel Target being developed

Source-Output-Limited Beams (Ni, Zr, Sn)

ION	Energy (MeV/u)	Intensity (pnA)	Power (W)
58-Ni	160	40	371
64-Ni	140	15	134
96-Zr	120	3	37
112-Sn	120	10	120
118-Sn	120	3	38
124-Sn	120	3	44

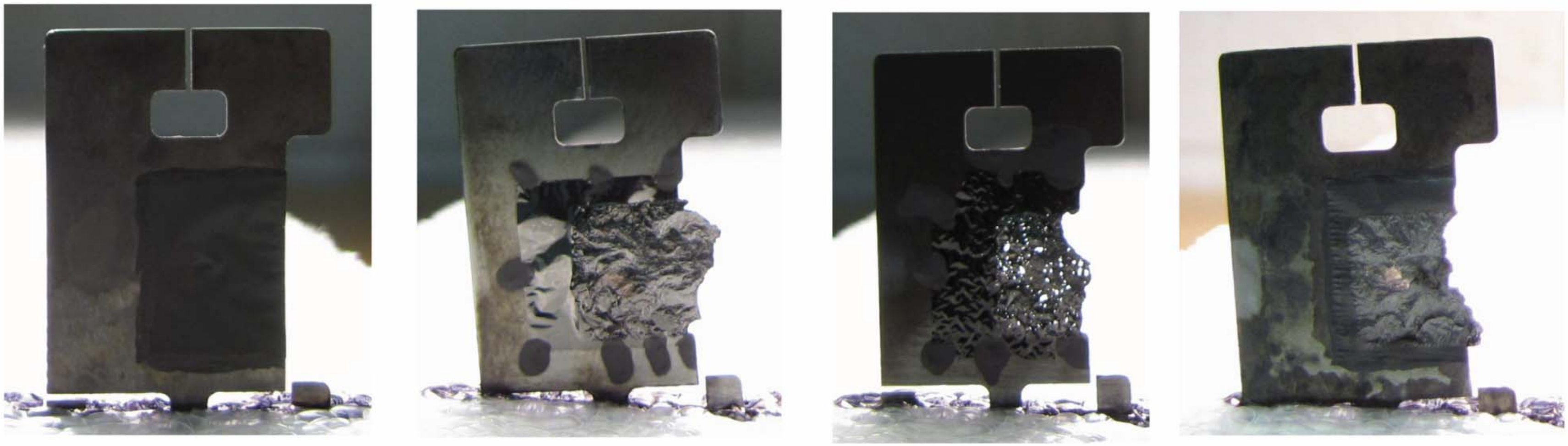
(However for all Beams, Higher Brightness is a plus)

Foil-Limited Beam Intensities

ION	Energy (MeV/u)	Intensity (pnA)	Power (W)
208-Pb	85	2	36
209-Bi	80	2	34
238-U	80	.3	6
238-U	45	.1	1

Foil Degradation with 600 enA $^{238}U^{30+}$ (7.7 MeV/u) after 15 seconds!

NSCL Stripper Foil Experience



Unexposed MicroMatter KEK ACF

To be discussed in detail by

Felix Marti

Later this conference

Progress since Cyclotrons07

2006/2007

	^{16}O	^{48}Ca	^{78}Kr	^{124}Xe
Final (MeV/u)	150	140	150	140
Beam Power (W)	1500	1000	1000	400
K500 out / K500 in	**21%**	**37%**	**15%**	**28%**
K500 Defl. Loss	113 W	78 W	180 W	79 W
K1200 out / K1200 in	**34%**	**63%**	**49%**	**53%**
K1200 Defl. Loss	484 W	111 W	380 W	110 W
K1200 out / K500 in	**6%**	**22%**	**6%**	**14%**

2009/2010

^{16}O	^{48}Ca	^{78}Kr	^{124}Xe
150	140	150	140
1500	1000	1000	400
50%	**51%**	**36%**	**43%**
106 W	37 W	68 W	36 W
66%	**66%**	**61%**	**57%**
290 W	140 W	112 W	88 W
20%	**33%**	**30%**	**25%**

(Normalized by beam to the same final output power)

NSCL

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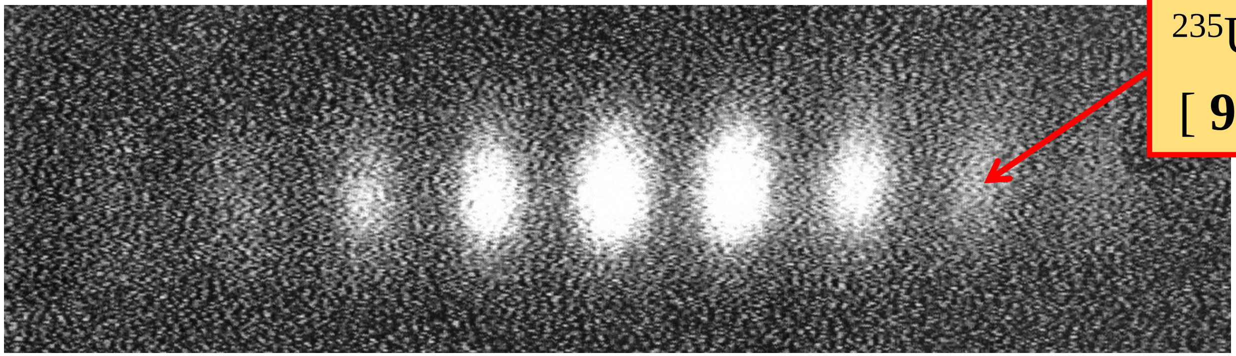
(Normalized by beam to the same final output power)

Stripping Efficiencies of K1200 Foil

K1200 Transmission percentages are given with the stripping efficiency normalized to 100% to allow comparison between beams of different ions.



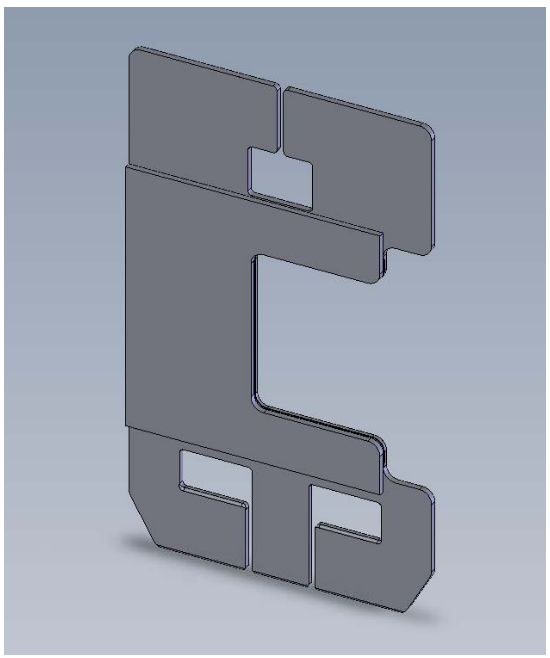
$^{235}U^{30+} \rightarrow {}^{235}U^{69+}$

[**9%** efficiency]

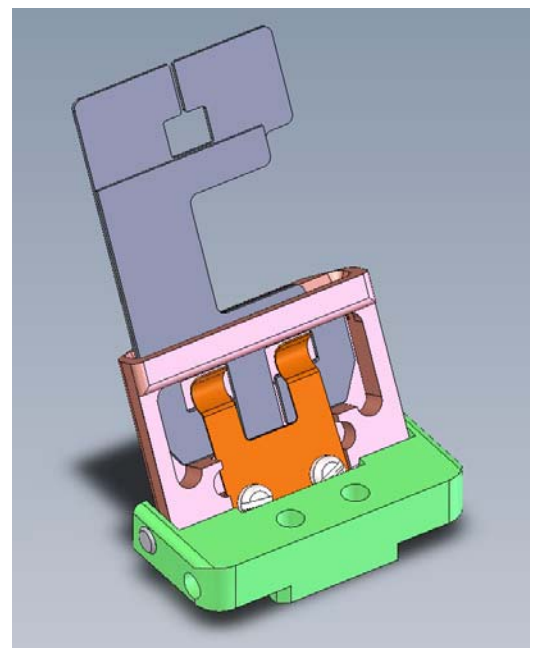
Stripping Efficiencies are measured for each beam, foil thickness, and foil type with a test setup in the K500 to K1200 coupling line.

Measured Stripping for 600 ugm/cm^2 Carbon

	^{16}O	^{48}Ca	^{78}Kr	^{124}Xe	^{238}U
Q1→ Q2	3+ → 8+	8+ → 20+	14+ → 34+	19+ → 45+	30+ → 69+
Efficiency	**95%**	**69%**	**53%**	**26%**	**9%**



(Foil Holder)



Intense Beam Operation of the MSU/NSCL Cyclotrons

Not Very??

1.2 kW of 140 MeV/u ^{48}Ca vs. Stainless Steel

Thickness of Vacuum Chamber wall = 9.5 mm

Range of 140 MeV/u ^{48}Ca in steel = 3.1 mm

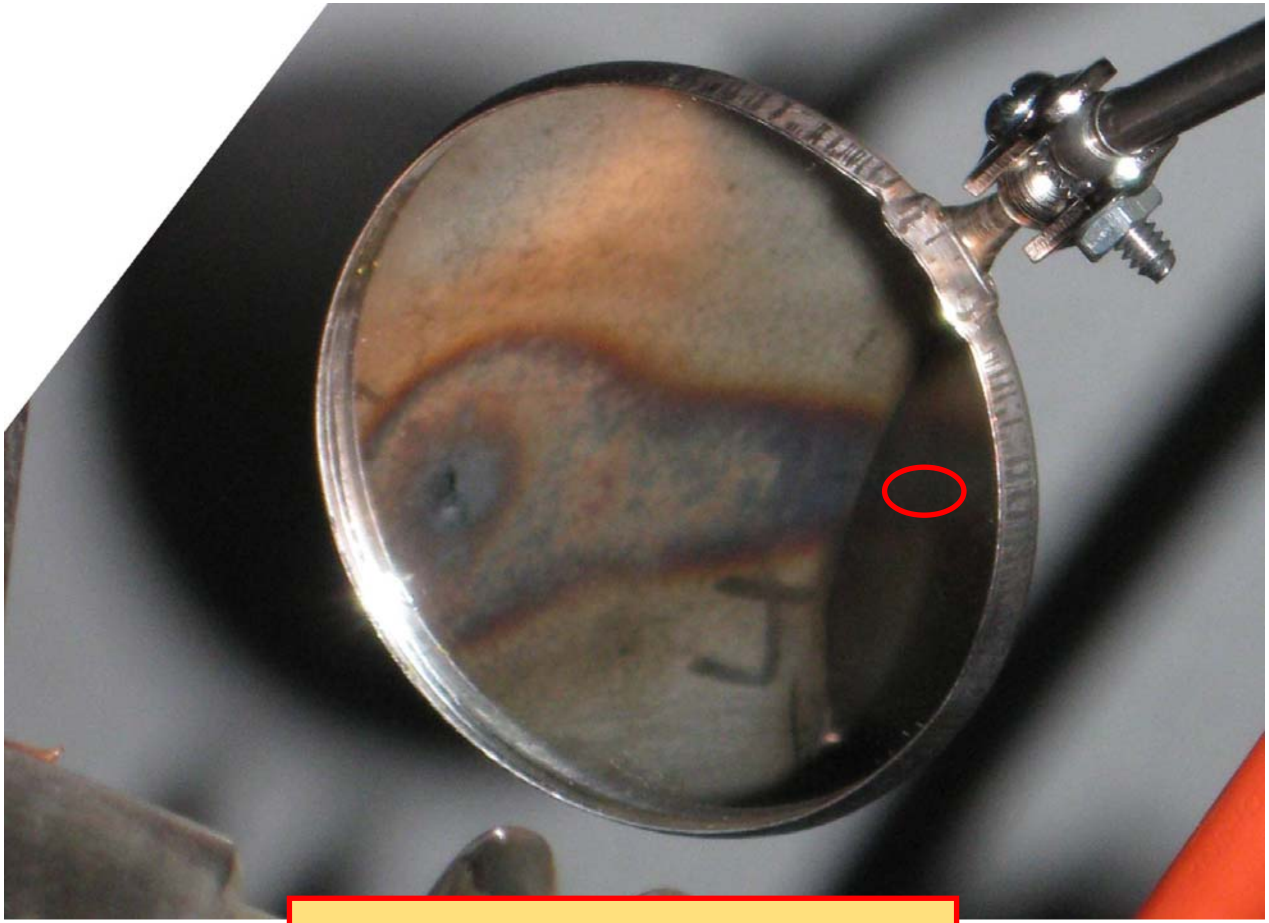
From the Operations Log:

"It is possible, but not likely,

that this vacuum event was not related to the beam,

but this operator doubts it."

Beam Wins



Event Duration < 20 sec

NSCL

Range/Energy (re-)Defines “Intense”

	MeV/u	Power	Range in Steel
Proton	590	1 MW	**275 mm**
^{48}Ca	140	1 kW	**3 mm**

(Material Damage effects are also more severe with increasing ion mass.)

These beams must be tuned and run ***cautiously***


3 Key
Elements of
Making
Intense Beam

Deflectors are a *Major* Concern

Short Range of Heavy Ions
In Materials

+

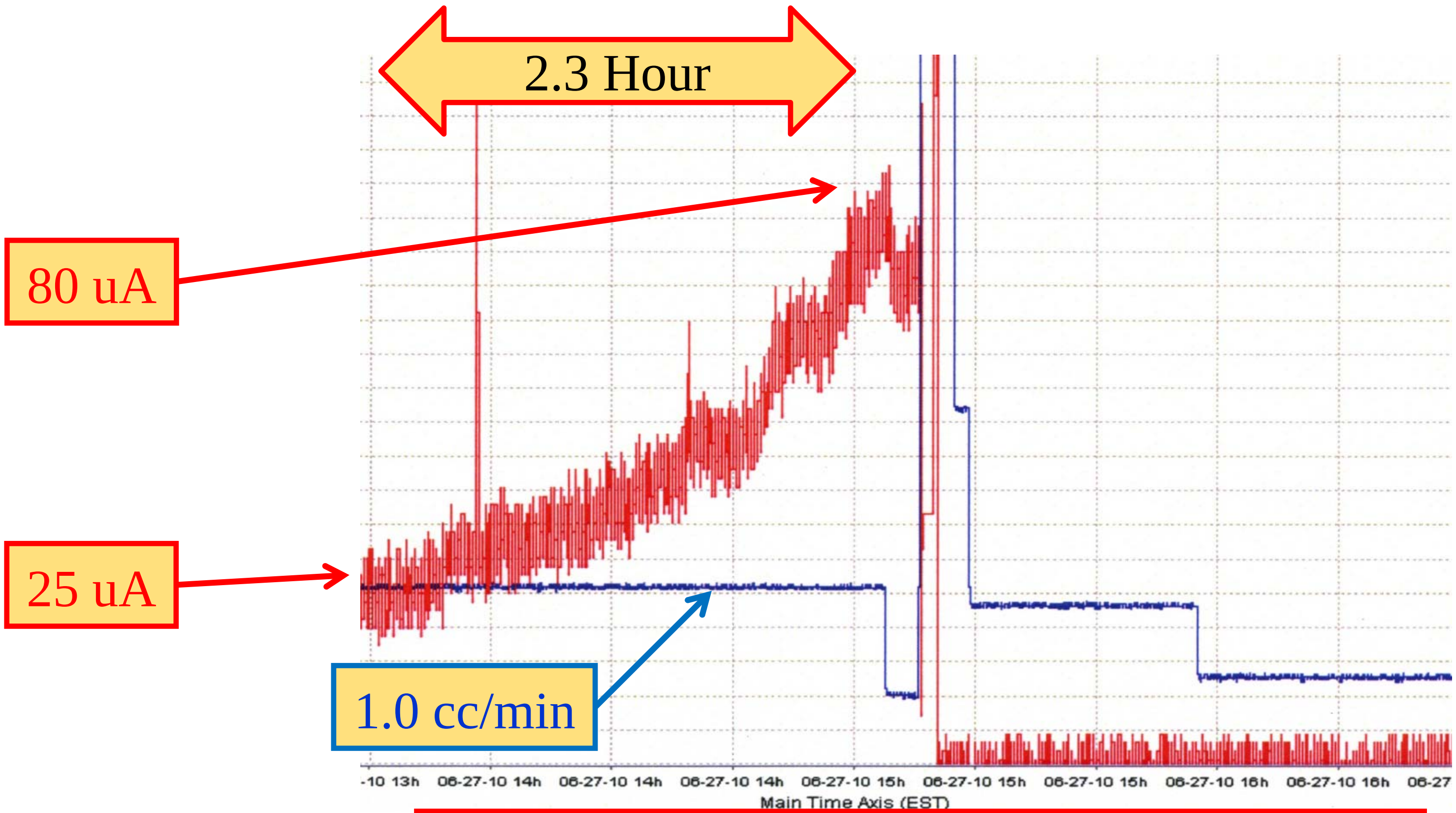
Full Radius Turn Separation
(beam center-to-center):
K500 ~ 1.3 mm
K1200 ~ 0.65 mm

+

~ 100 kV/cm electric Field
In
Deflectors

=

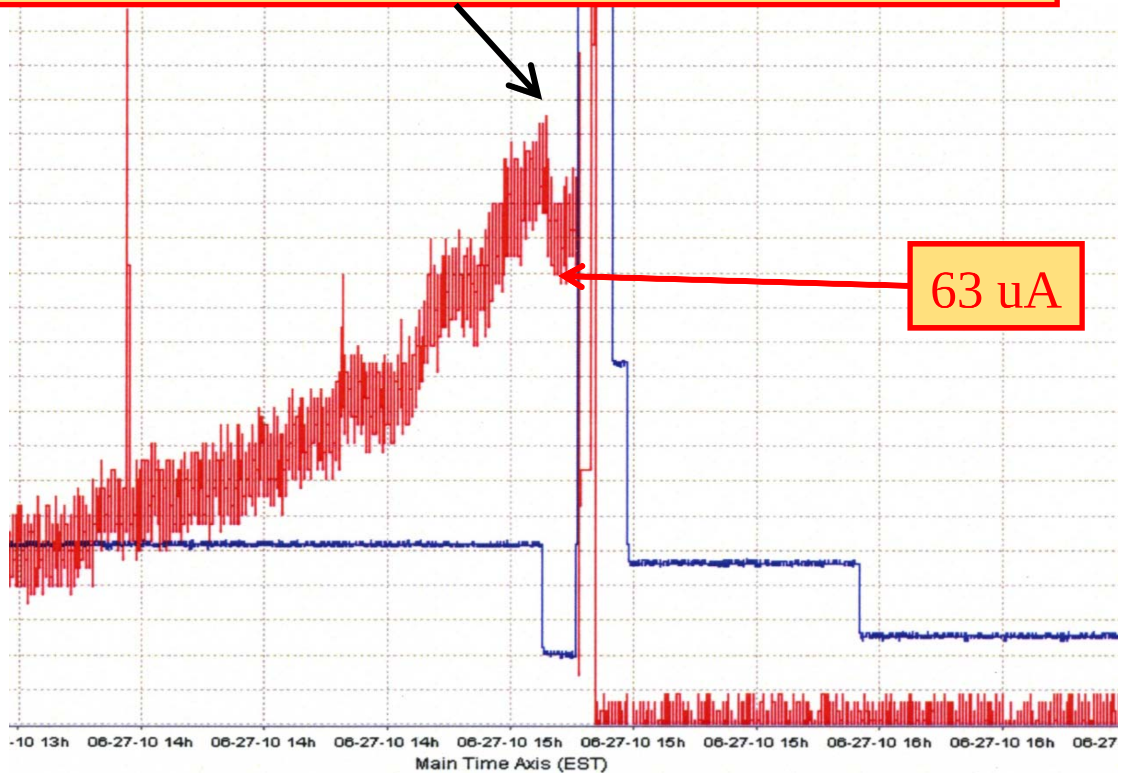
Key #1: O_2 Gas Flow during Operation



O_2 flow (in standard cm^3/minute) vs. Deflector power supply current (µA)

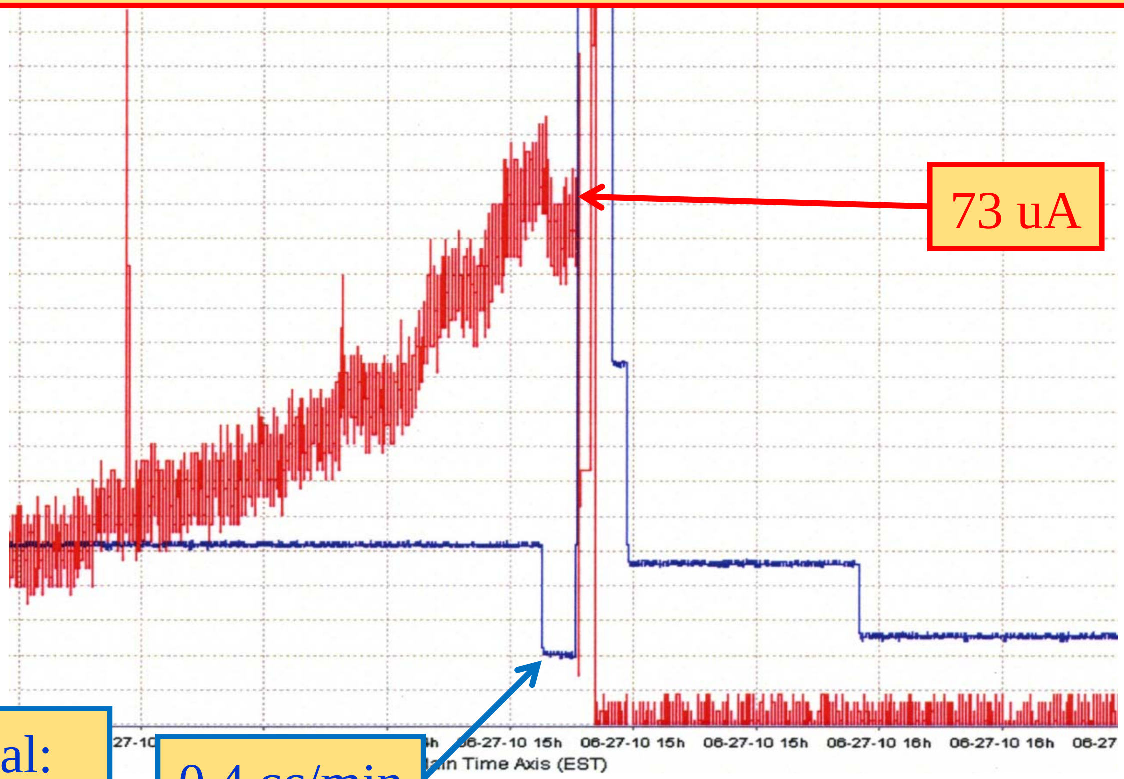
O_2 Gas Flow, Beam Off

Operator stops beam → Current falls slightly



O_2 Gas Flow, Beam Off

Flow lowered to more-normal value → Current trends up

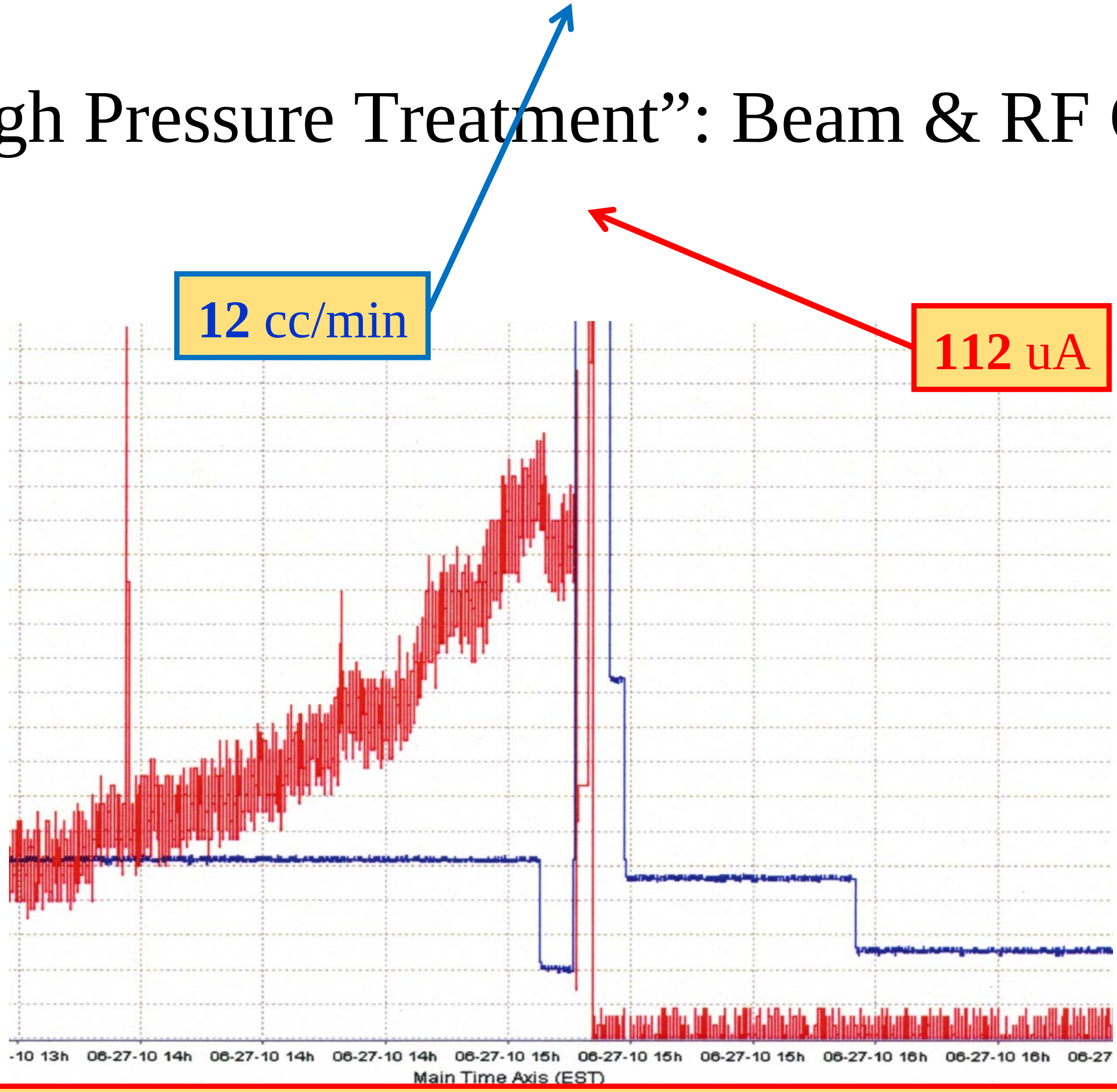


73 uA

(normal: 0.2 cc/min)

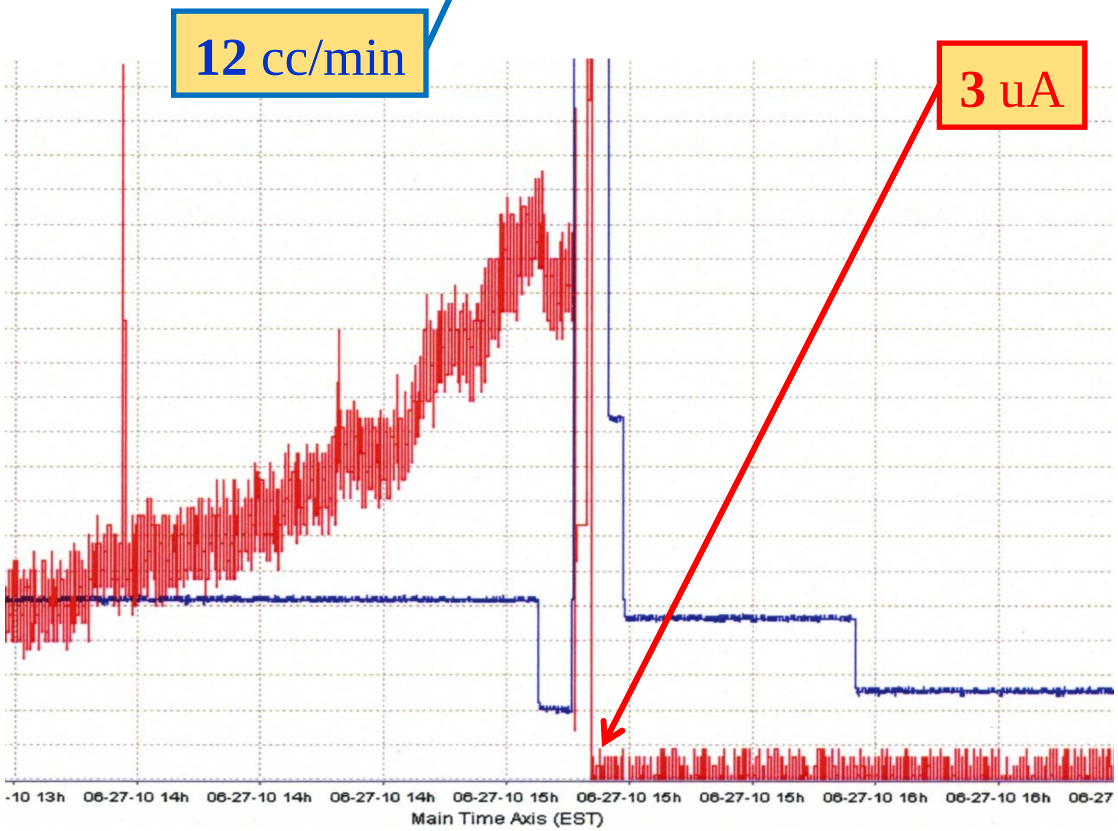
0.4 cc/min

“High Pressure Treatment”: Beam & RF Off

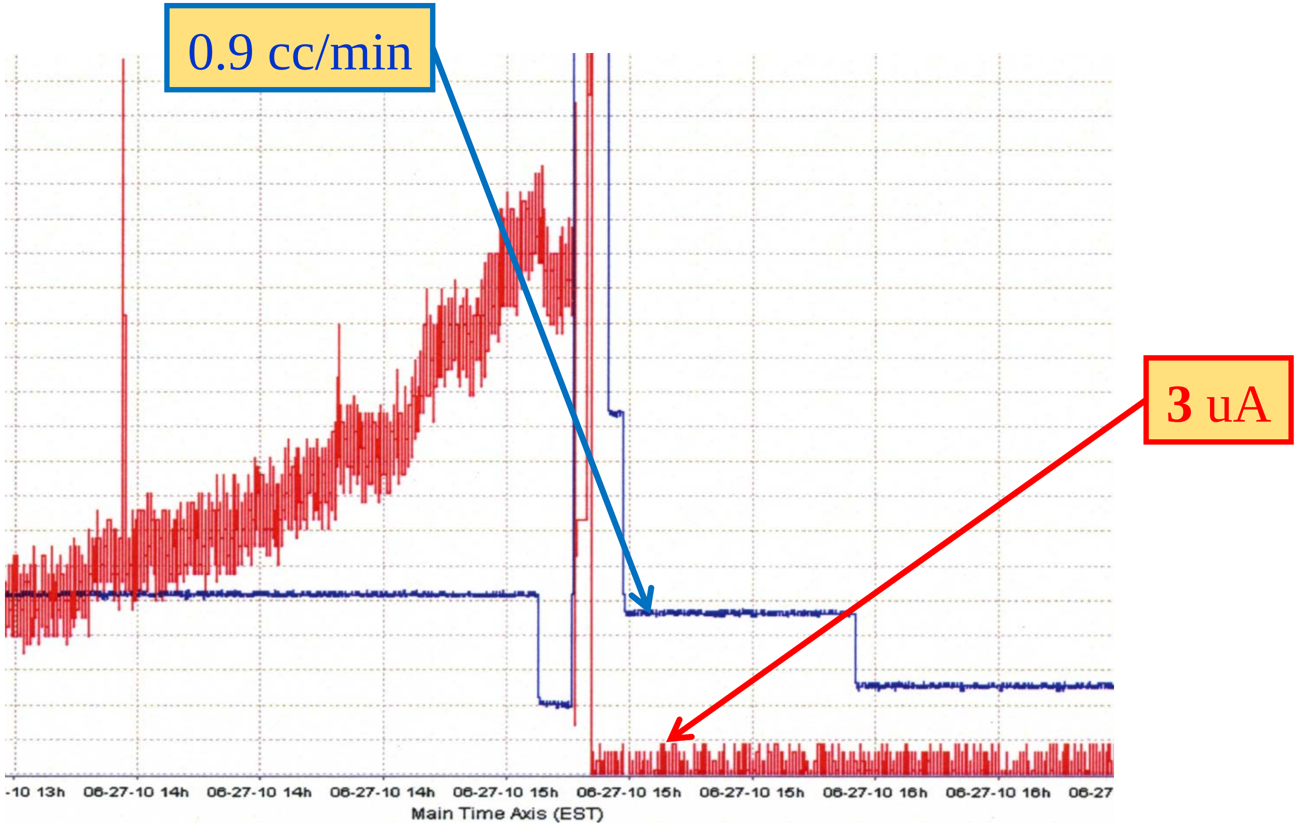


Deflector voltage set high, but gets into a low volts/high current (corona?) Discharge

“High Pressure Treatment”: Beam & RF Off



Normal Operation Resumed: Time Lost = 20 minutes



Key #1: O_2 Gas Flow during Operation

Allows Recovery of normal Deflector function

Without venting/removal/cleaning

How this works = ?

May be similar to

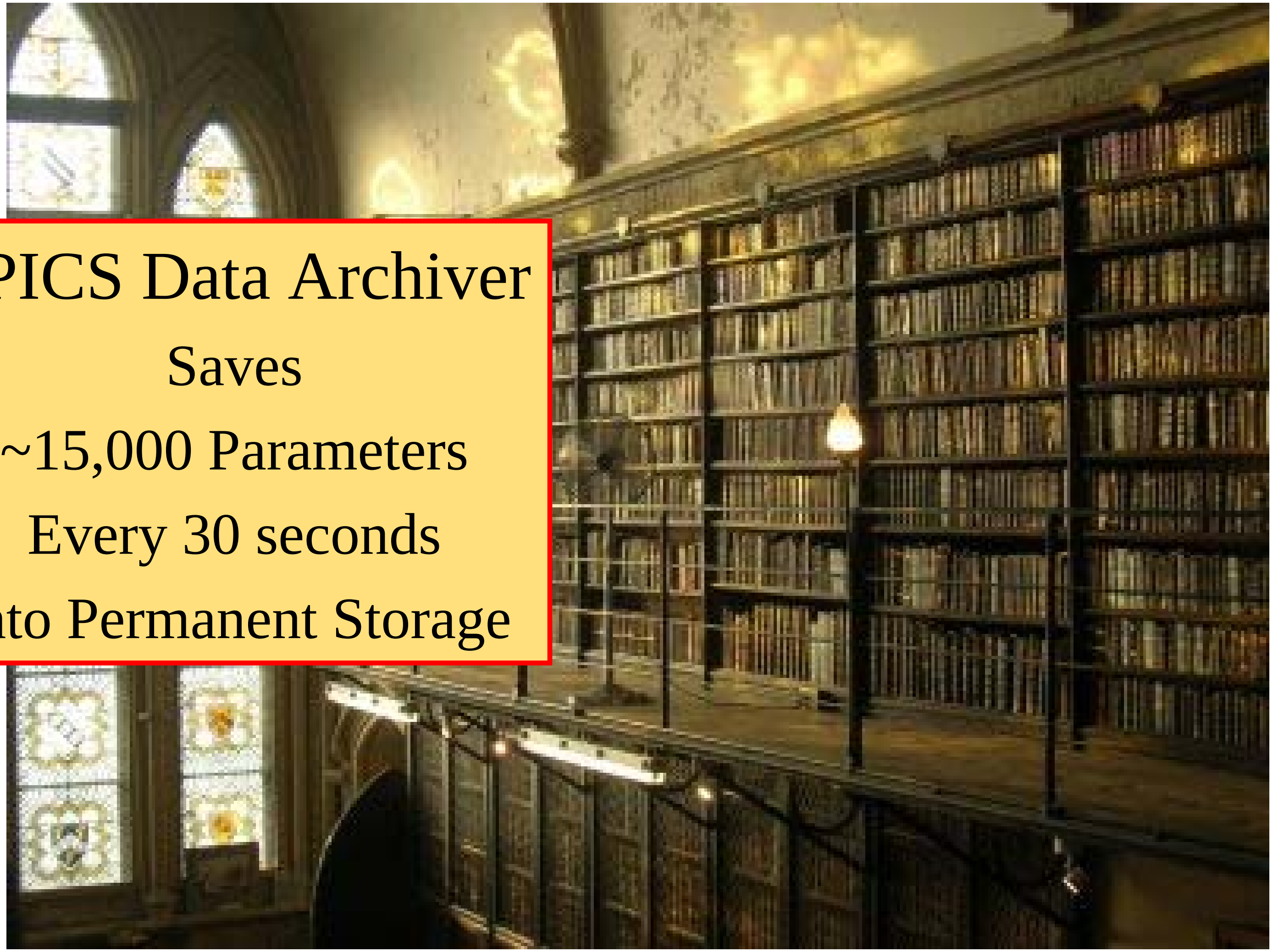
“**Oxygen Plasma Cleaning**”

“**Oxygen Plasma Cleaning**”

Gives

131,000 Google Hits

Useful Aside: Event Reconstruction



EPICS Data Archiver

Saves

~15,000 Parameters

Every 30 seconds

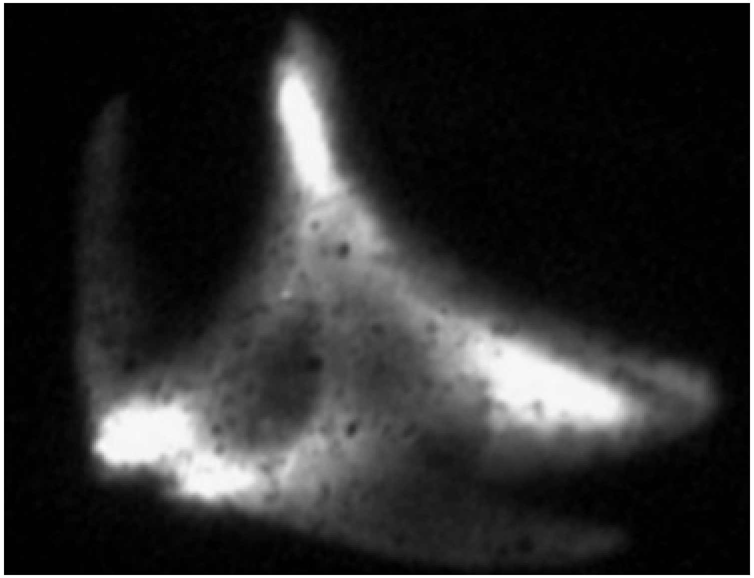
Into Permanent Storage

Key #2: Low Emittance Injection

Year	16-Oxygen On K500 Inflector (euA)	Extracted Beam (euA)
2002	100	1.1
2006	5.0	1.1
2010	2.1	1.1

Better transmission through the cyclotron =
Many fewer problems

"Don't inject what won't extract"
Not easy with ECRIS Beams



NSCL Image of $^{16}O^{3+}$

Presented Tokyo 2004

The Beam characteristics from ECRIS's are a poor match for injection Into Accelerators

Good Emittance can be Achieved (and it's vital to do so)

For NSCL Artemis ECRIS techniques see in particular:
J. W. Stetson, NSCL, *Proceedings of ECRIS08*, Chicago, IL, USA (JACoW, 2009), THCO-A03, p. 189.

For NSCL SUSI ECRIS techniques see:
G. Machicoane, NSCL, this conference!

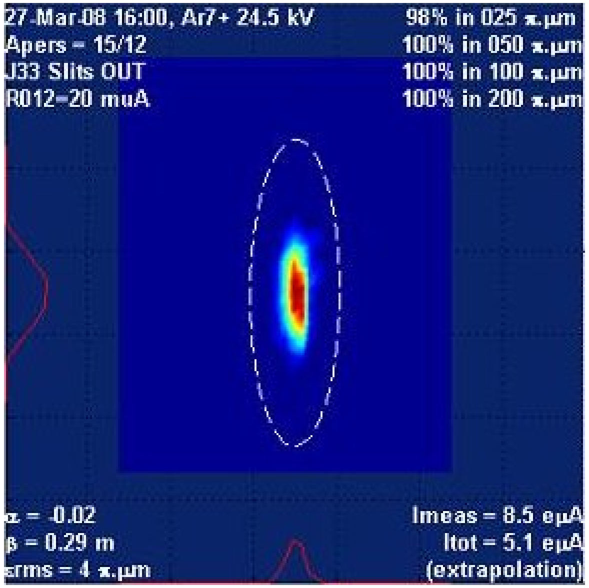
ECRIS beam quality is an active area of investigation at every Heavy-Ion Beam Lab, so there are *many* other important references now available

Injection Conditions for Intense NSCL Beams

1) Beam Emittance < 20 π mm*mr (rms) (best < 10 π mm*mr) @ 18-27 kV*q keV with Intensity of 10 – 20 e μ A

2) Minimal Beam "Tails"

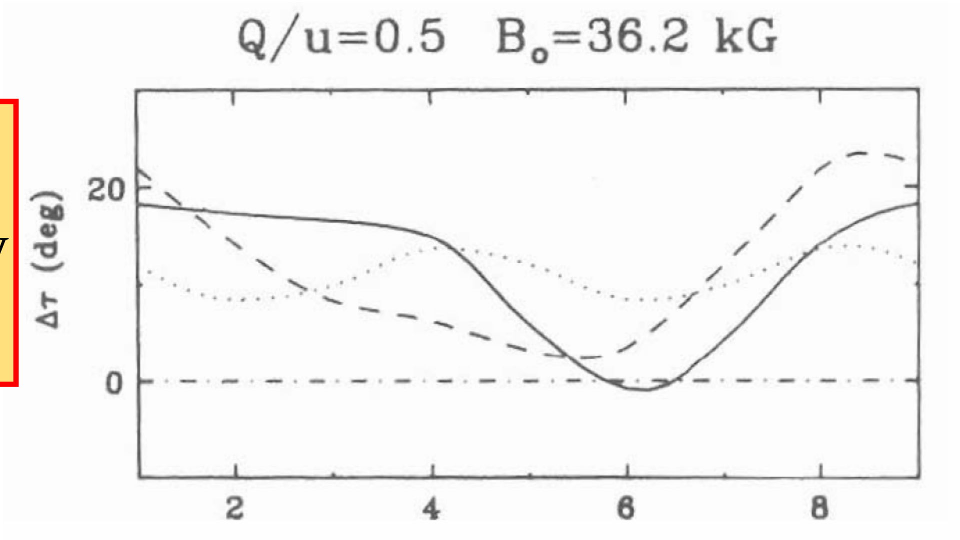
3) Medium charge state (~5 < M/Q > ~ 8)



($^{40}Ar^{7+}$ ~10 e μ A 4 π mm*mr rms)

High Emittance Spreads Bunched Phase width thru K500 Inflector

Spiral Inflector *widens*
100 π mm*mrad bunched beam by
40 deg (in 2nd harmonic operation)



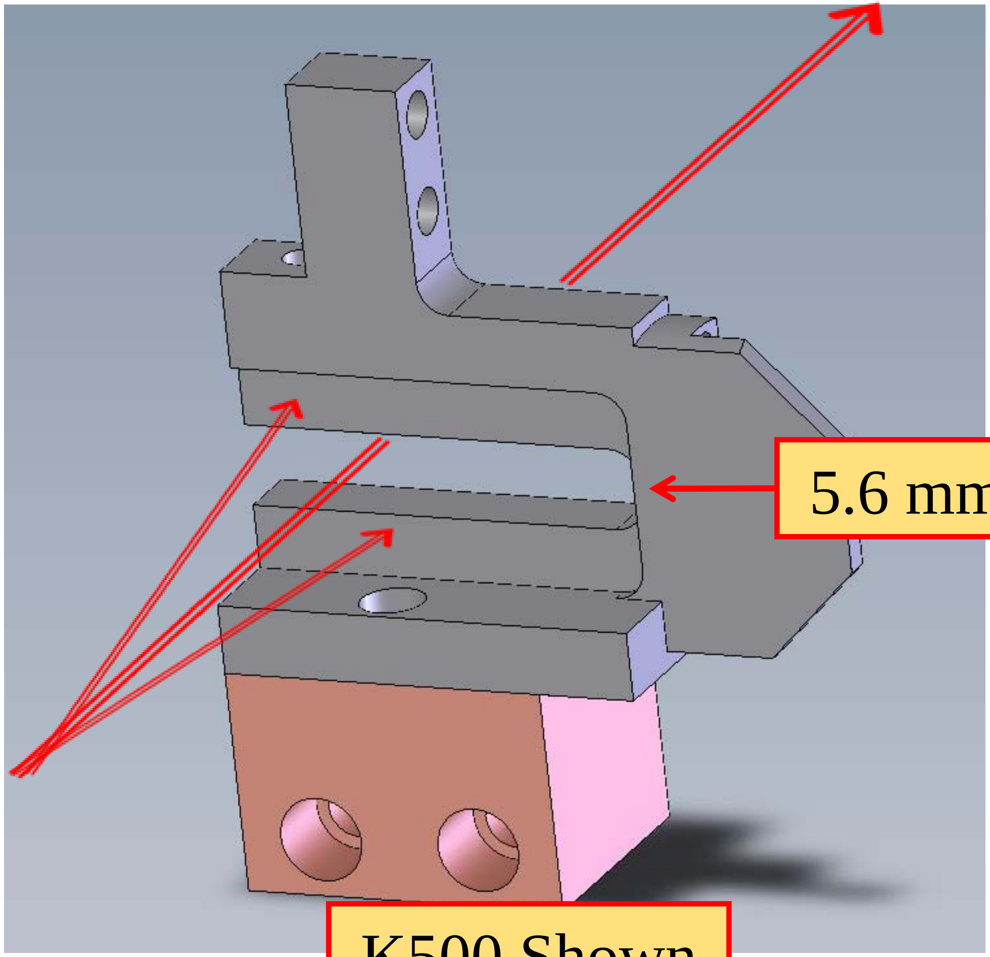
Minimized emittance gets
Minimal Phase spread

F. Marti, IEEE Trans. On Nucl. Sci., vol. NS-32, No. 5, Oct. 1985

Key #3: Scraper / Collimator

Vertical collimation of the last few orbits

Trims vertical beam blowups caused by the $\nu_r = 2\nu_z$ resonances present in K500 and K1200

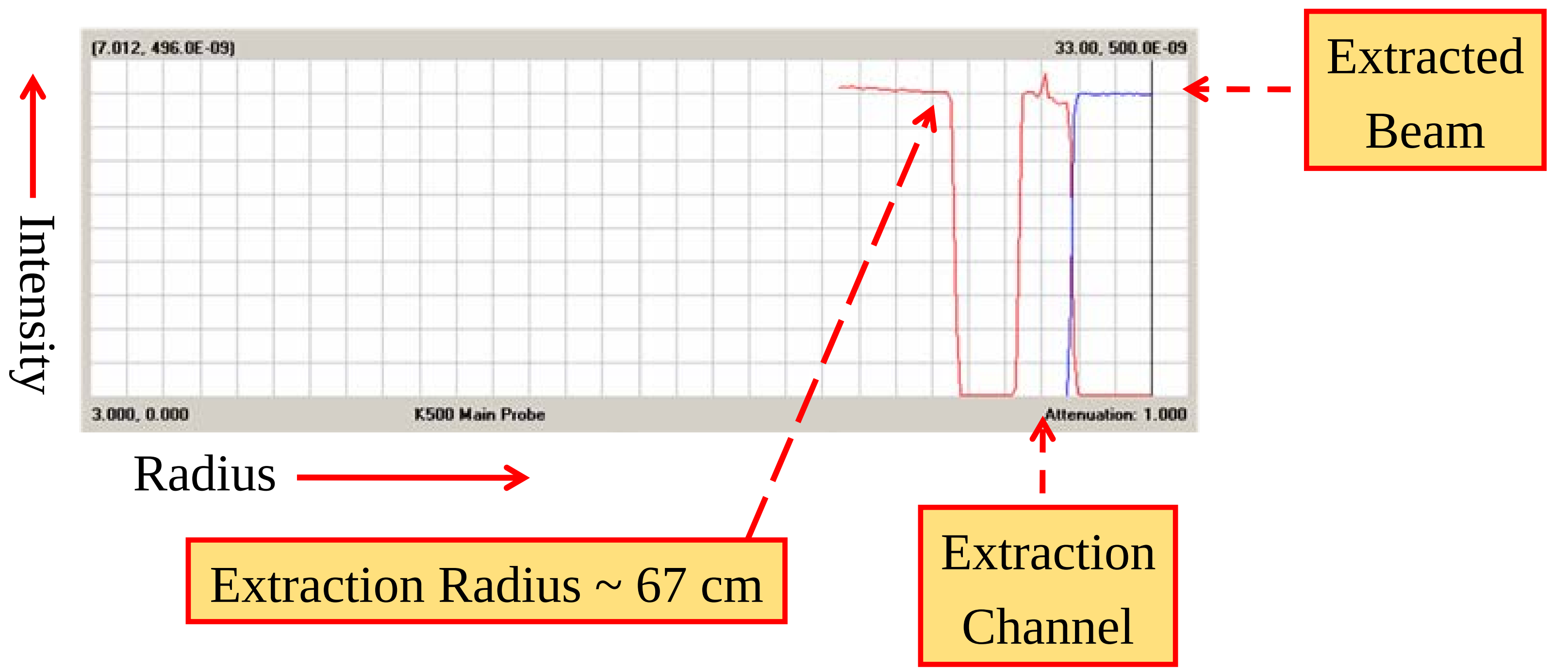


5.6 mm gap

K500 Shown

Perfect $^{40}Ar^{7+}$Beam = No Scraper Losses

K500 Radial Probe Trace



K500 out / K500 in = 62%
100% extraction efficiency

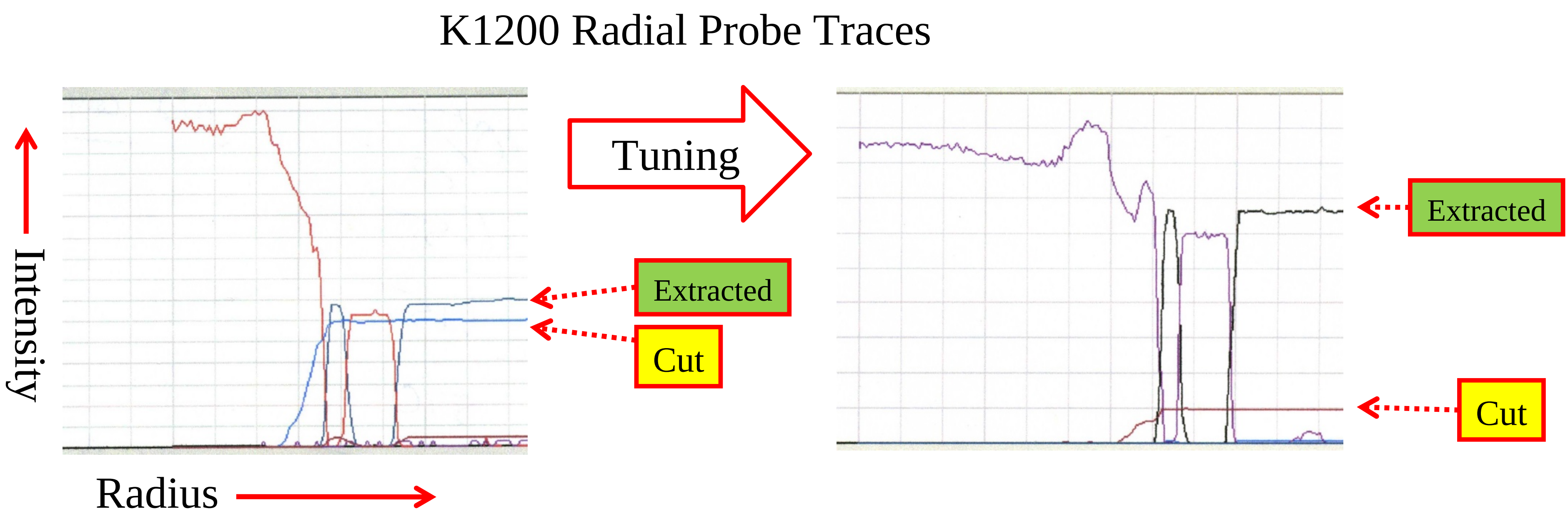
“Unclean” Injection $^{208}Pb^{27+}$ = Losses

K500 Radial Probe Trace

The low output of ^{208}Pb from Artemis
Limited collimation in the
Injection Line → high emittance

K500 out / K500 in ~ 25%
50% extraction efficiency

Key #3: Scraper / Collimator (K1200)



Off-Center Beam is Cut by the Collimator:

1) Decouples the effect of centering and extraction “bumps”

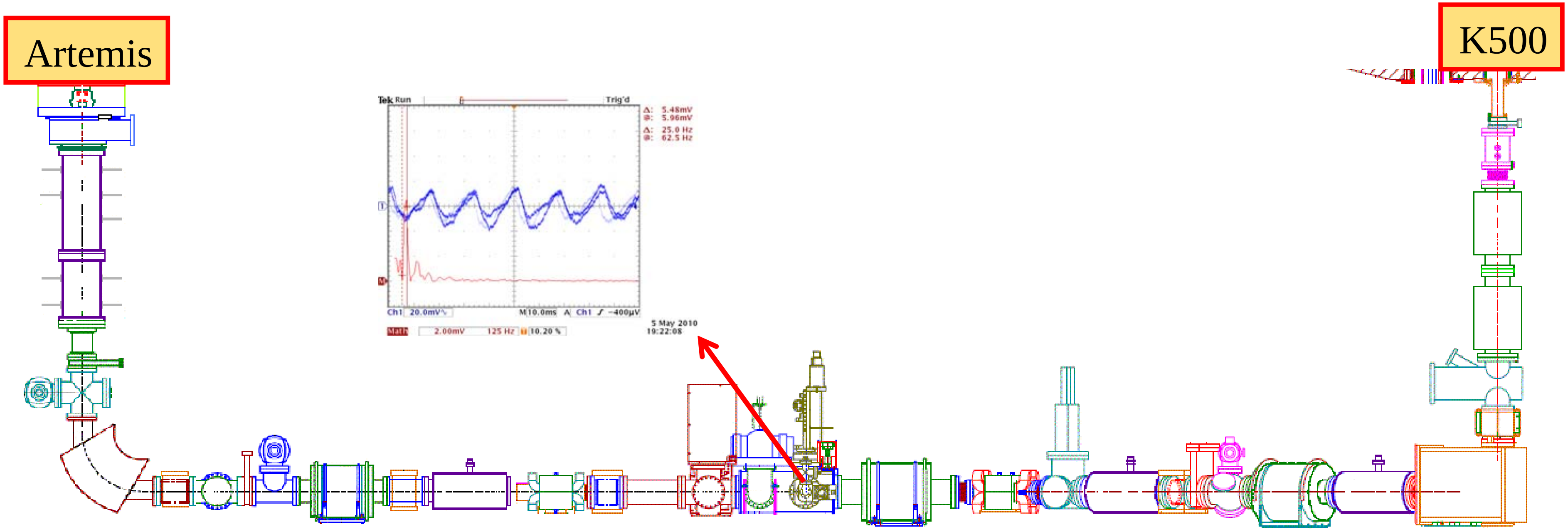
2) Reduces losses on the Deflector

3) K1200: deteriorating Foil → higher collimator losses


Further
Consideration(s)

Source Monitoring & Tuning Using FFT

ECRIS Beam is not Pure DC



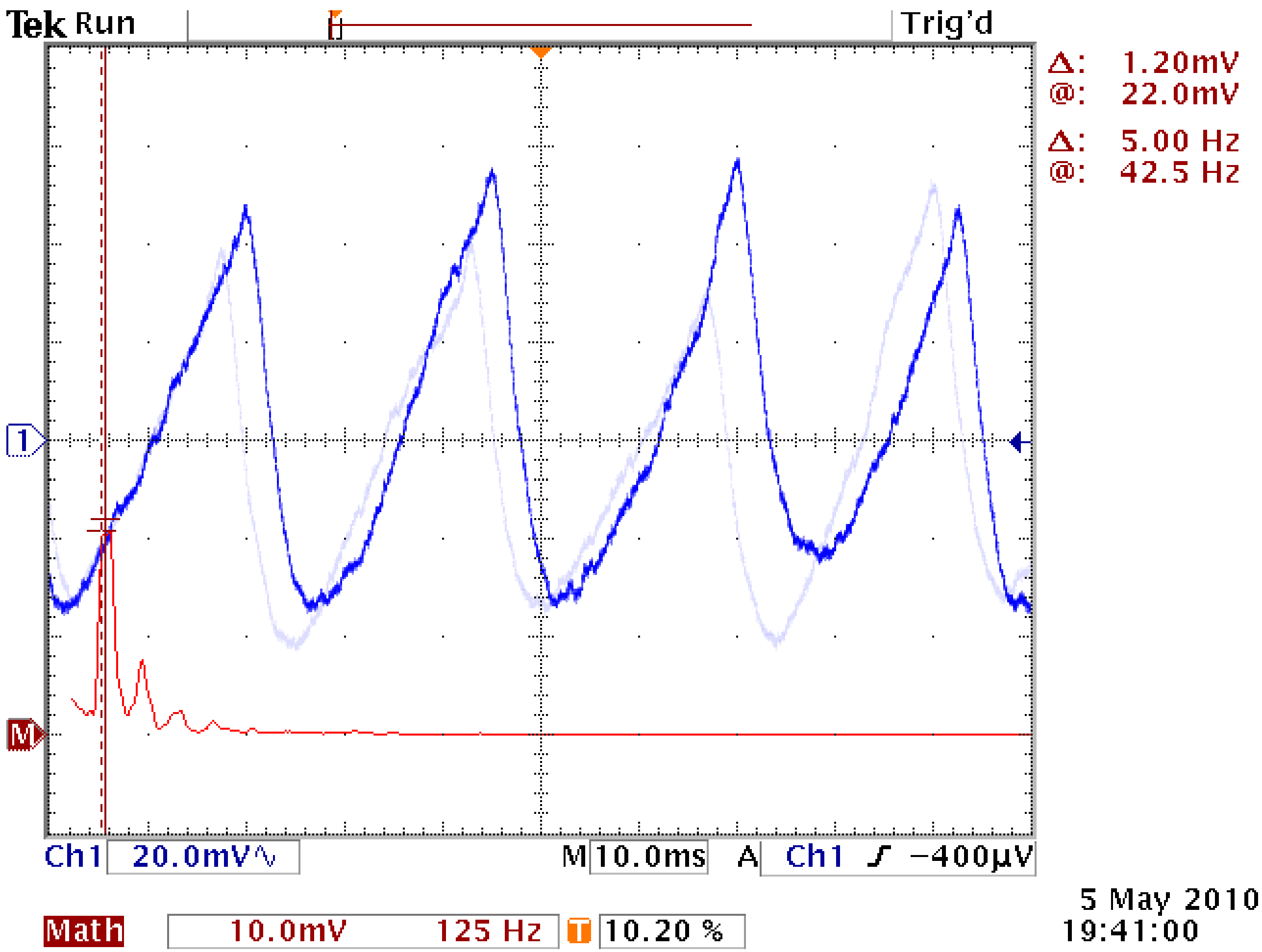
Look at a signal taken directly from a Faraday cup
or a Wire inserted into the beam path
using an FFT-analyzing oscilloscope

$^{40}Ar^{7+}$: Microwave power = 305 W

I = 65 uA

AC Noise = 2.7 %

Frequency = 43 Hz

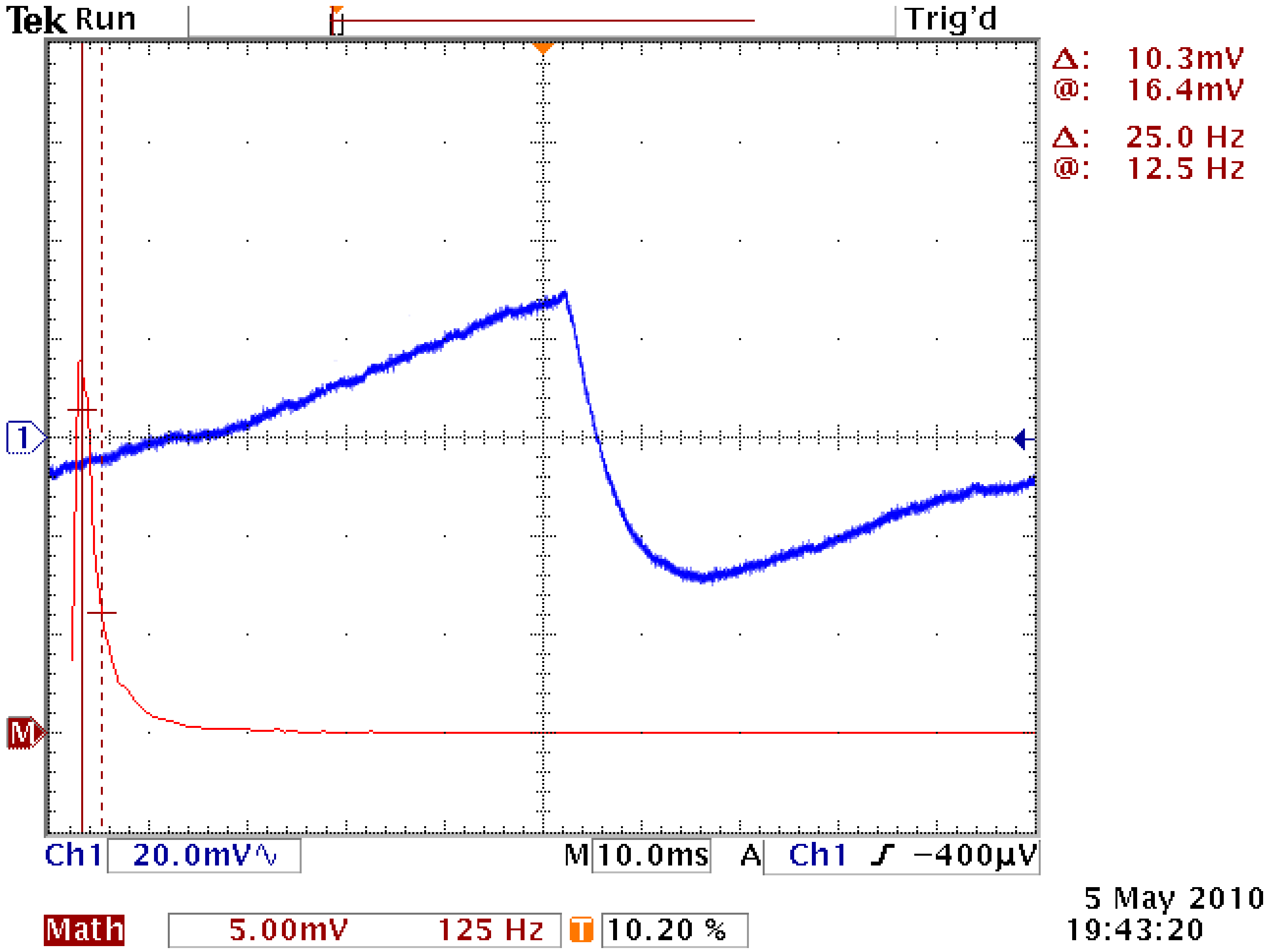


$^{40}Ar^{7+}$: Microwave power = 310 W

I = 50 uA

AC Noise = 1.9 %

Frequency = 12 Hz



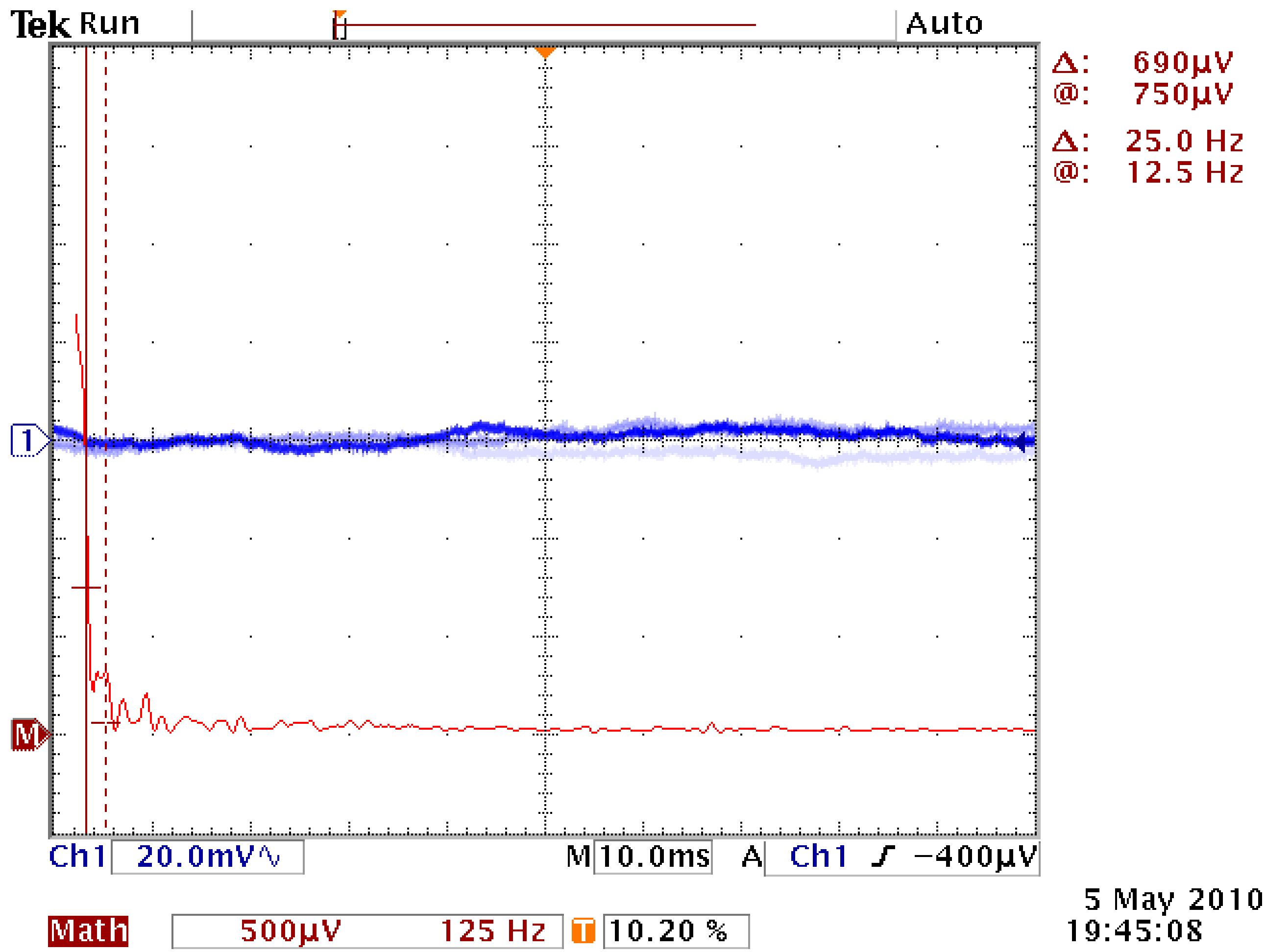
$^{40}Ar^{7+}$: Microwave power = 315 W

I = 50 uA

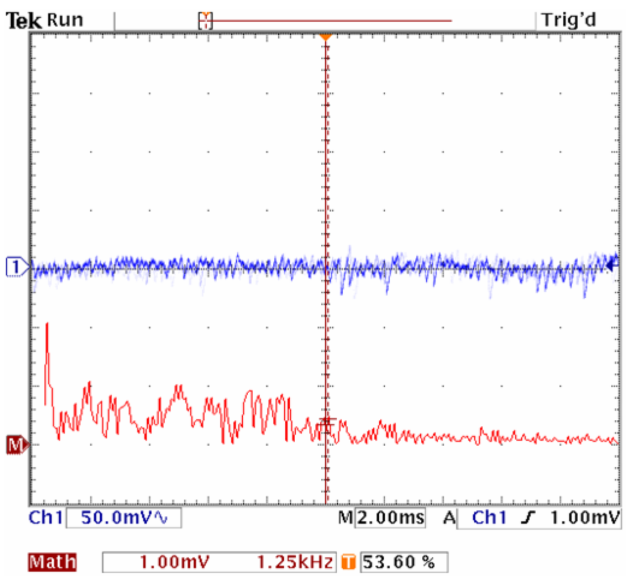
AC Noise < 0.1 %

Frequency = ? Hz

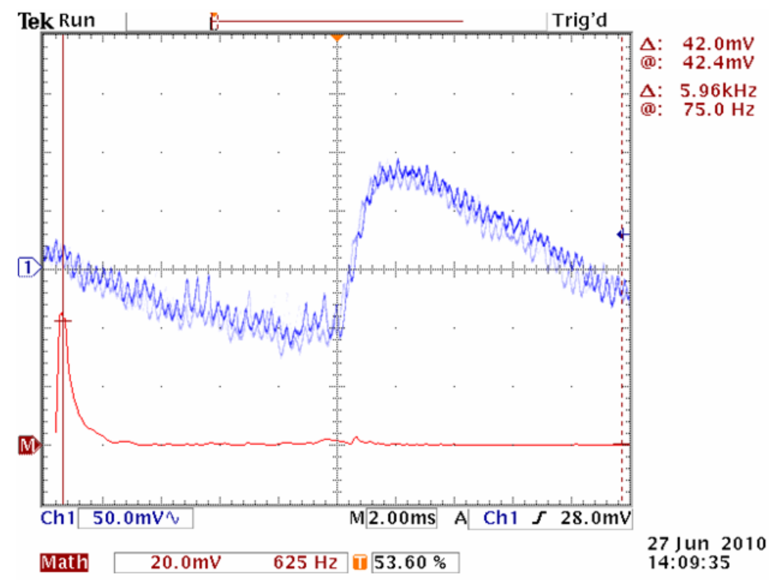
Best ??



Importance? “Mode” Influences Injection



Overnight
Drift

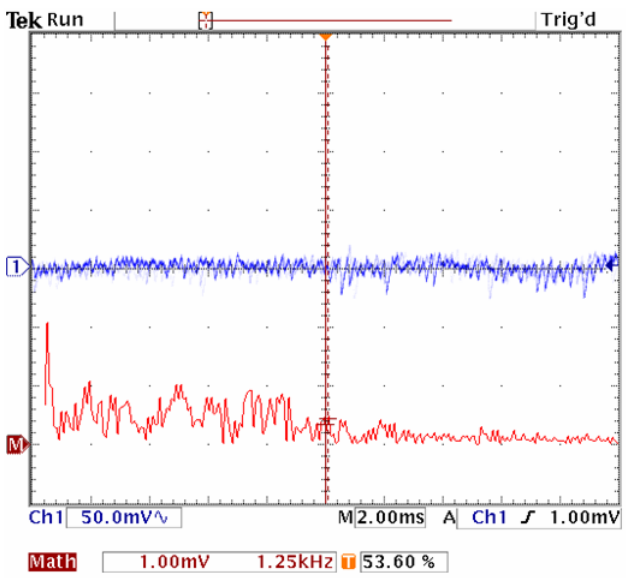


Good Beam
Thru
K500

Overnight
Drift

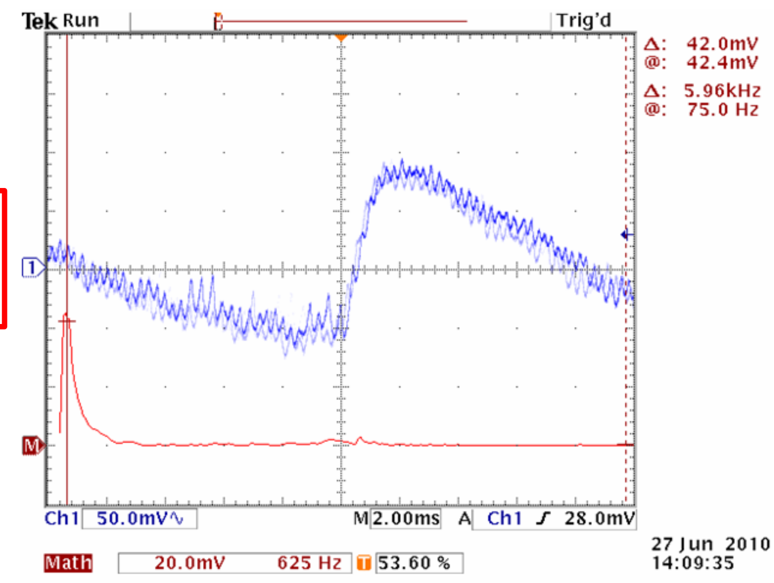
½ Beam Intensity thru
K500
(with similar source output)

Importance? “Mode” Influences Injection



Minor

Source Retune



Good Beam

Thru

K500

Minor

Source Retune

½ Beam Intensity thru

K500

(with similar source output)

Offers Easy Access to Plasma Condition

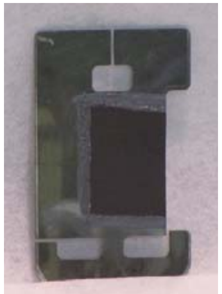
Some very provisional comments:

1) Which mode(s) give best Brightness? – Unknown
2) Low Freq. (<100 Hz) → quiet chaos → High Freq. (> 1 kHz)
3) Sensitivity to source parameters greater at high charge state
4) Modes vary among different charges of the same ion
5) Mode shifts may occur at "peaks" of beam output intensity

(All data taken with a low-pass filter cutoff of 1 MHz)

Wide Foil vs. Narrow Foil ($^{16}O^{3+} \rightarrow 8^{+}$)

(lightish ions are not fully stopped by the probe at high energy)



8 mm

3 mm

(1 mm shown)

Output = 2.4 euA, **720** W

Total Throughput = 42%

Extraction Efficiency = 49%

Deflector Power Loss = **480** W

Output = 5.2 euA, **1560** W

Total Throughput = 66%

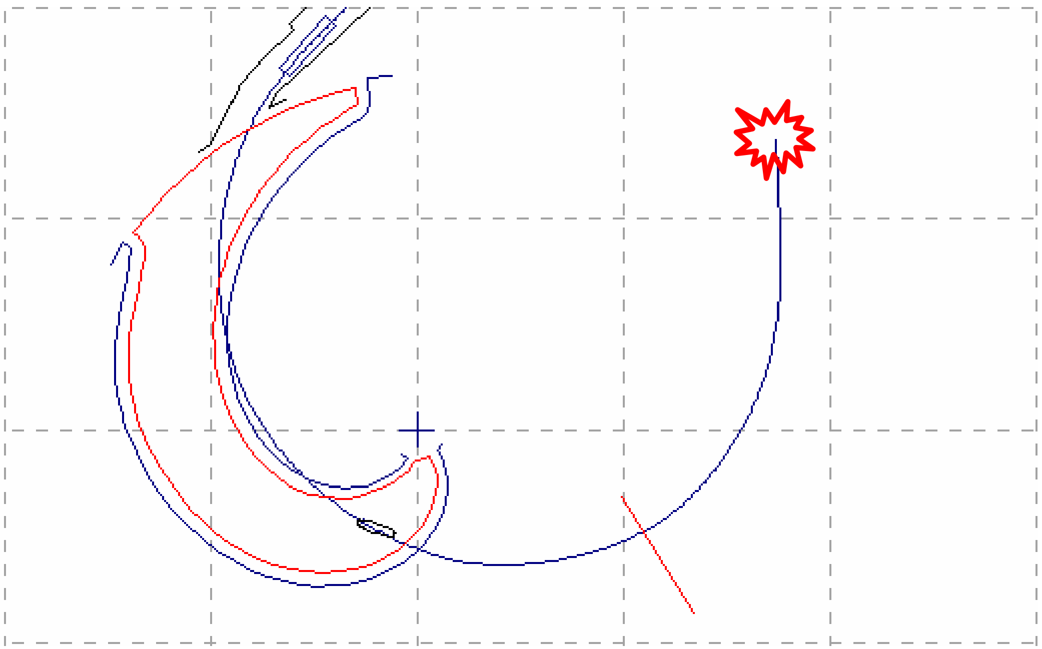
Extraction Efficiency = 75%

Deflector Power Loss = **304** W

K1200 Deflector Heating by Unstripped Beam

$^{16}O^{3+}$ Injected Beam Path

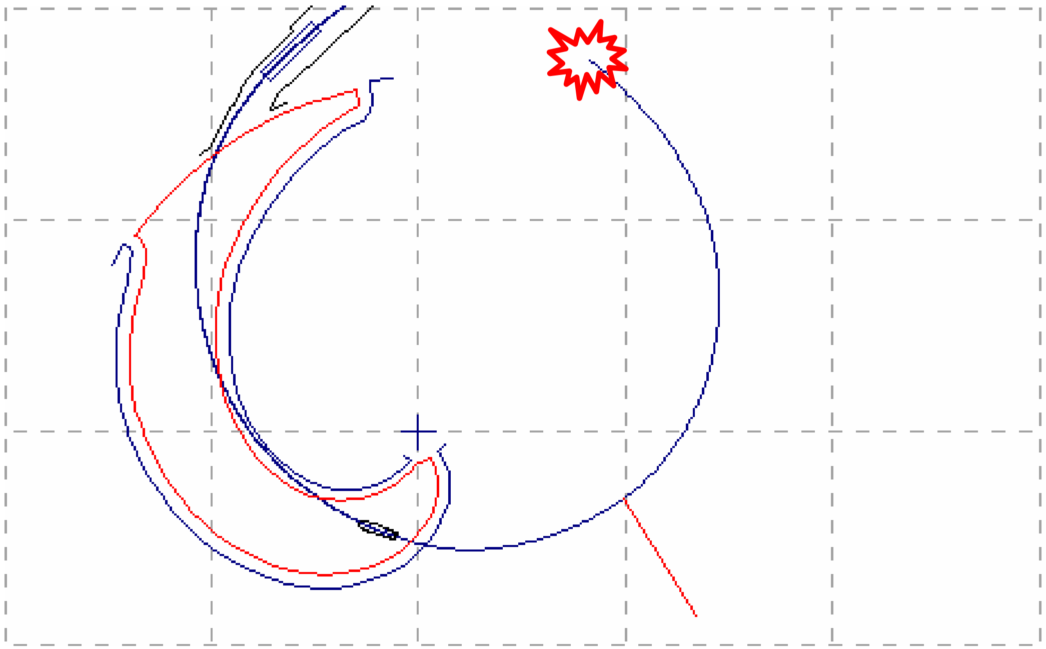
Beam that is
Not stripped
Hits dee edge
Strip ~ harmless



K1200 Deflector Heating by Unstripped Beam

$^{124}Xe^{19+}$ Injected Beam Path

Beam that is
Not stripped
hits Deflector:
BAD!



$^{124}Xe^{19+}$ Injected Beam Power = 400 W

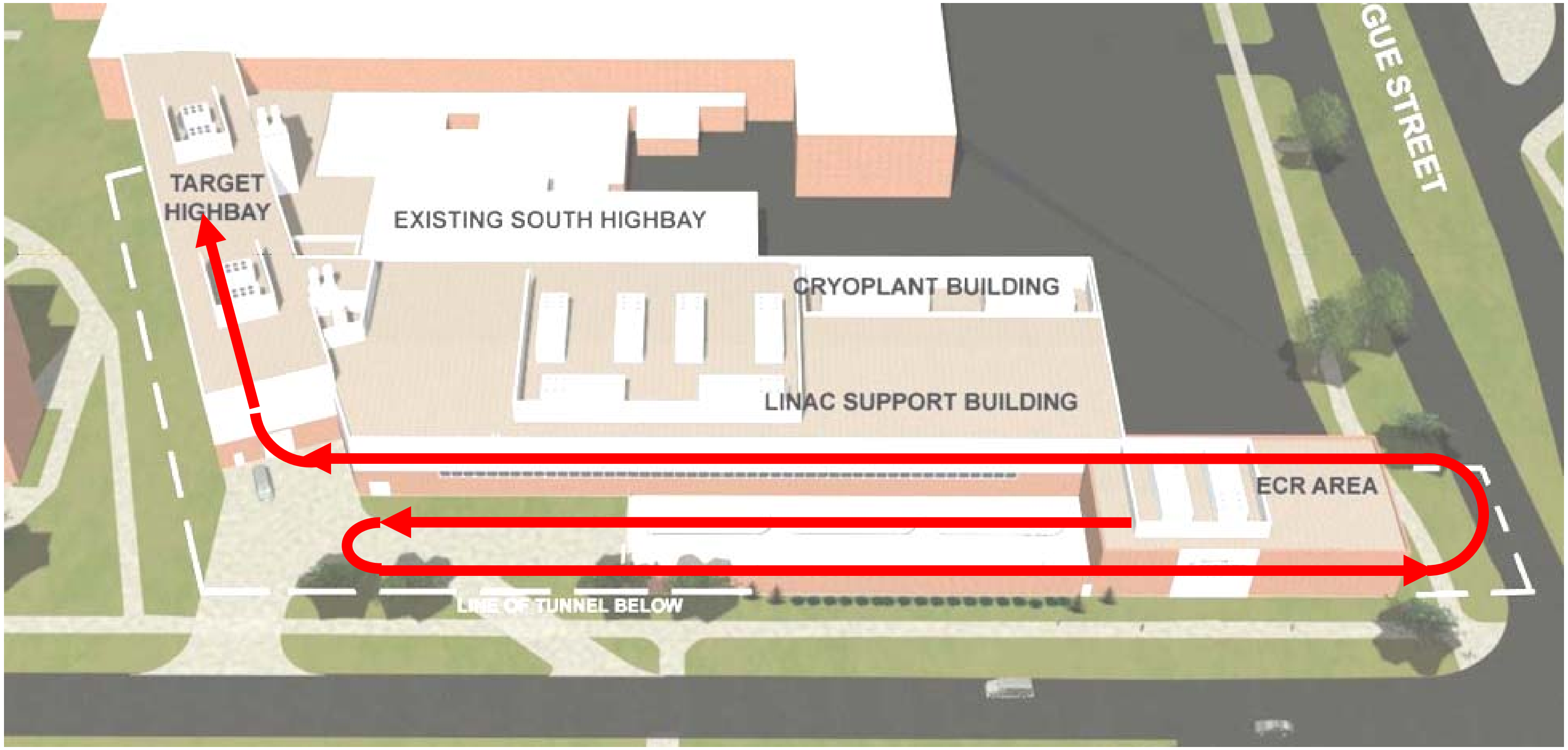
Summary

- Intensities for many beams ~ 800 – 1000 W
- ECRIS intensity increases (SUSI) → more power-limited beams
- Gradual improvement toward 2000 W (?)
- Experimental Demand is for ***much higher*** beam power

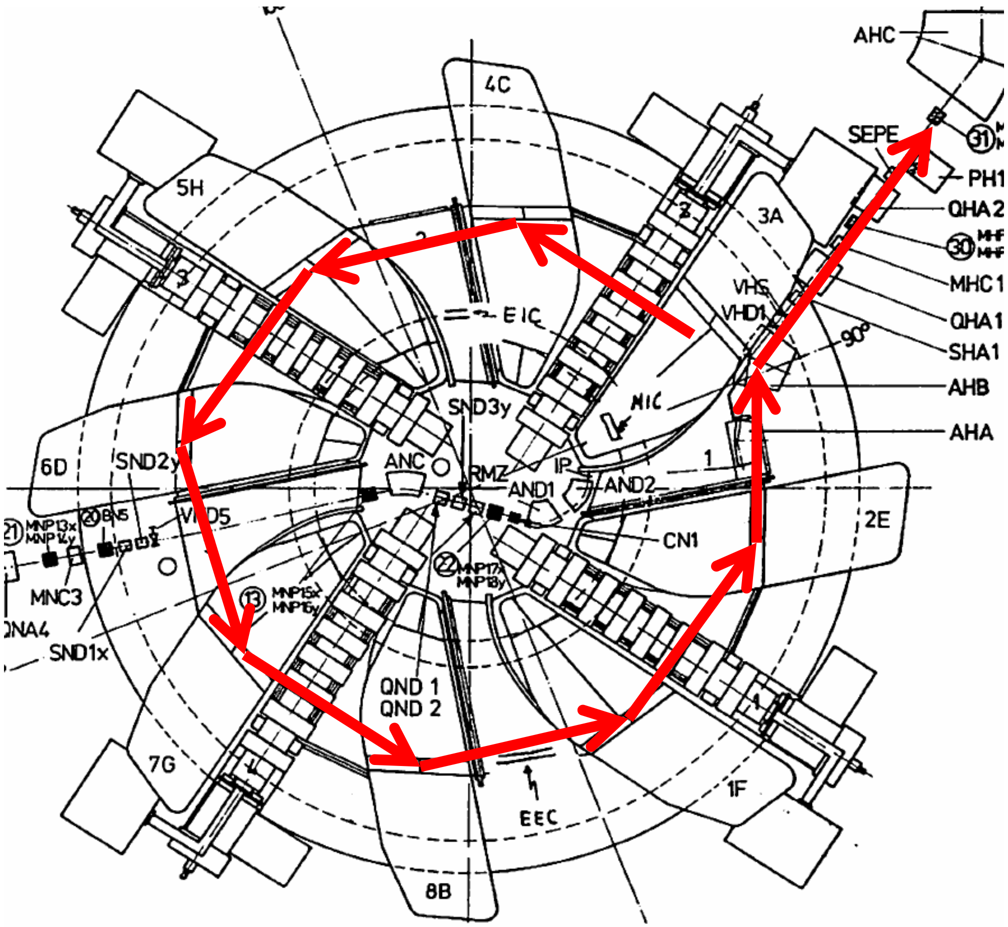
Major Upgrade Required

Ultimate Upgrade: FRIB Coming ~2018(?)

Bent Linear Accelerator: BLINAC



Logical Progression:
Separated-Sector *Linear* Cyclotron: SSLC



The Cast

OPERATIONS

- Peter Miller
- Mathias Steiner
- Andreas Stolz
- Operators!

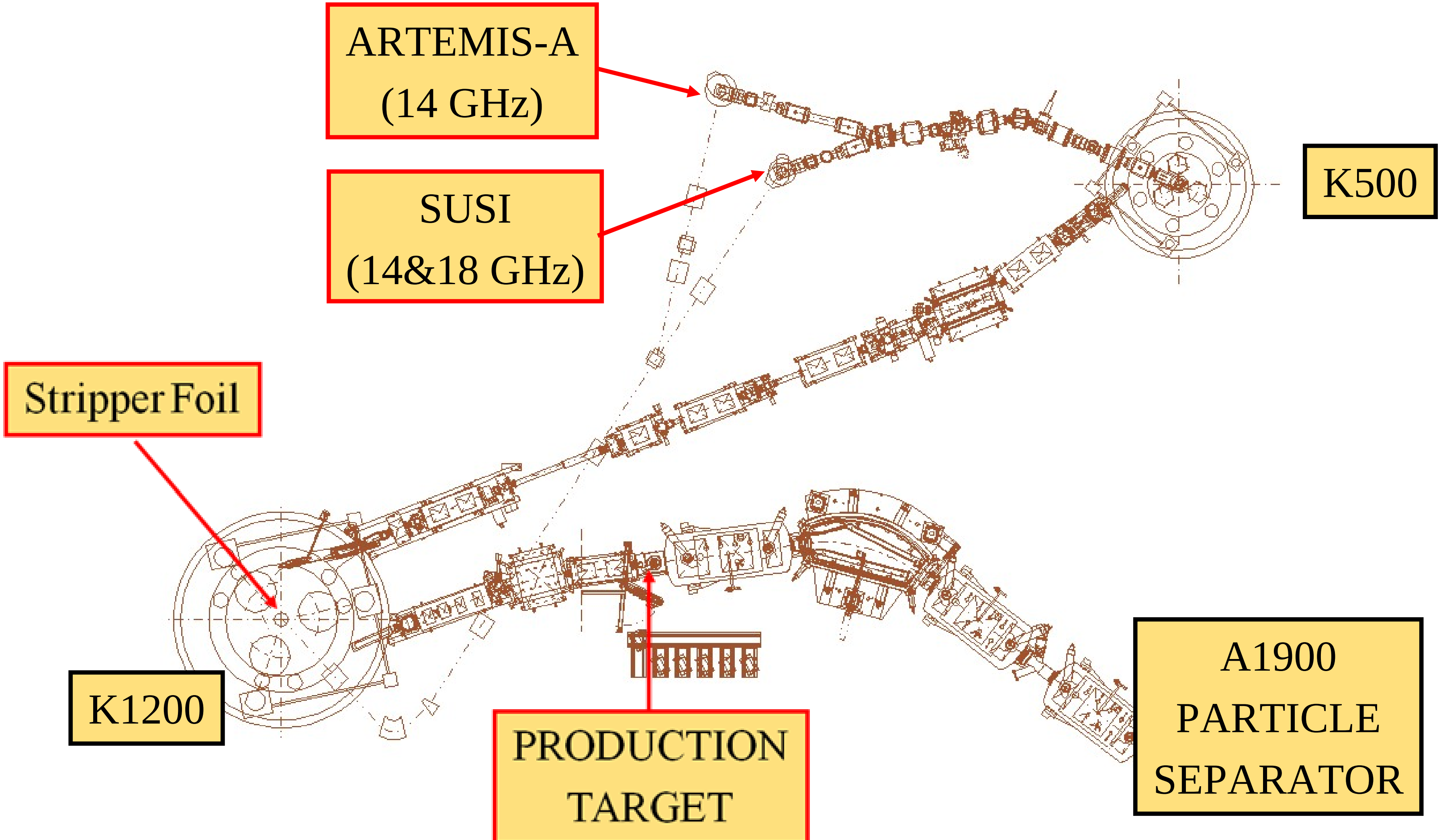
ION SOURCE

- Dallas Cole
- Larry Tobos
- Tommi Ropponen
- Liangting Sun

Thanks to:

- Peter Spaedtke, GSI
- Stefan Adam, PSI

Top View: Compact Machines
(K1200 Extraction Radius = 1 m)

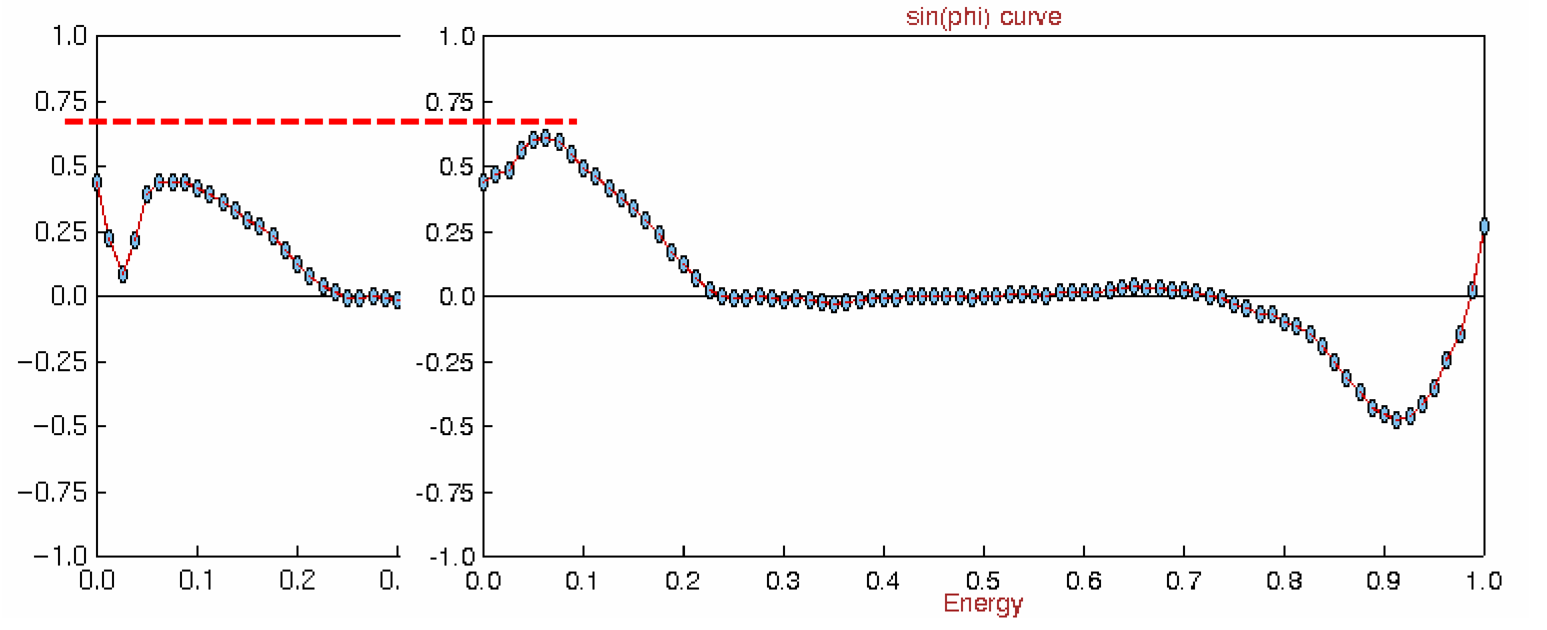


"Magnetic" Phase Compression

(1) Inject with phase error, (2) Bring back to 0 deg

Result: Increasing energy gain/turn

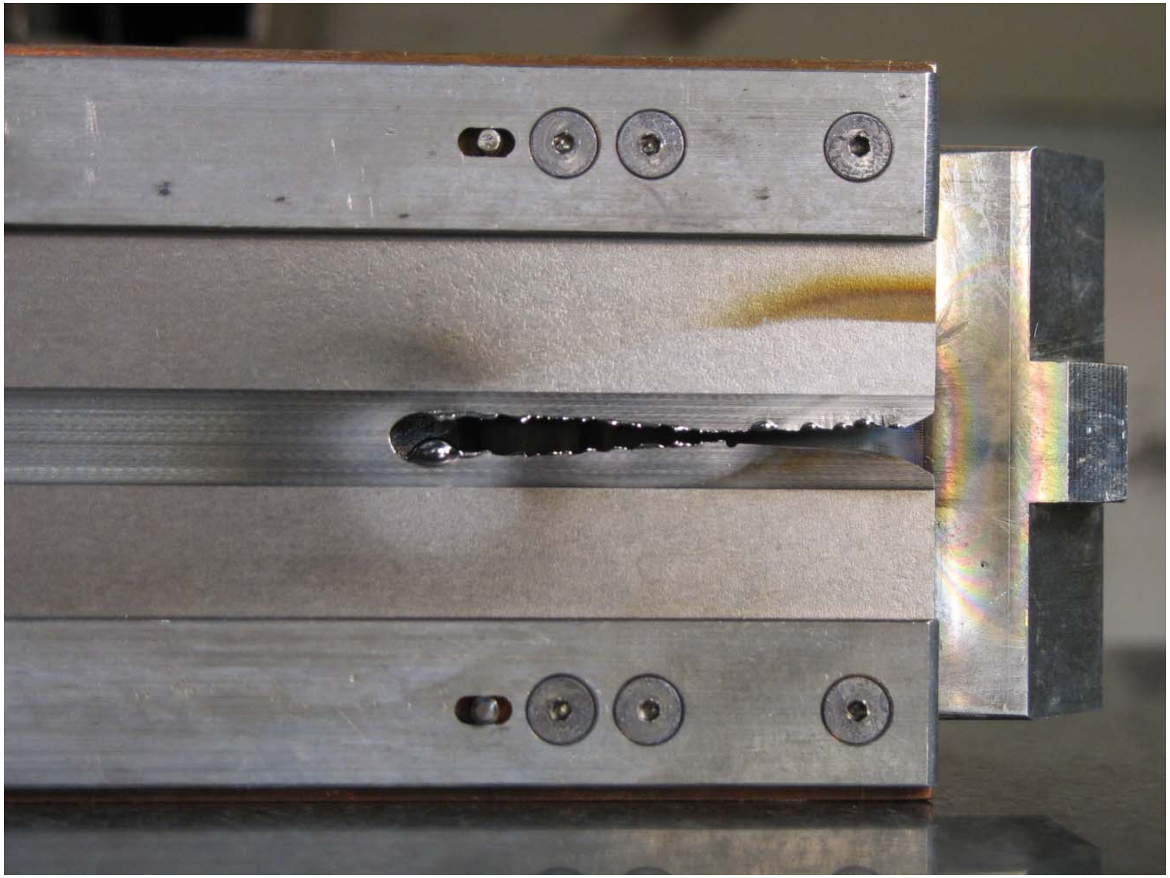
- Phase Compression -



A. Chabert, IEEE Trans. On Nucl. Sci., vol. NS-28, No. 3, June 1981

Exhibit A: K1200 Deflector Septum (Tungsten)

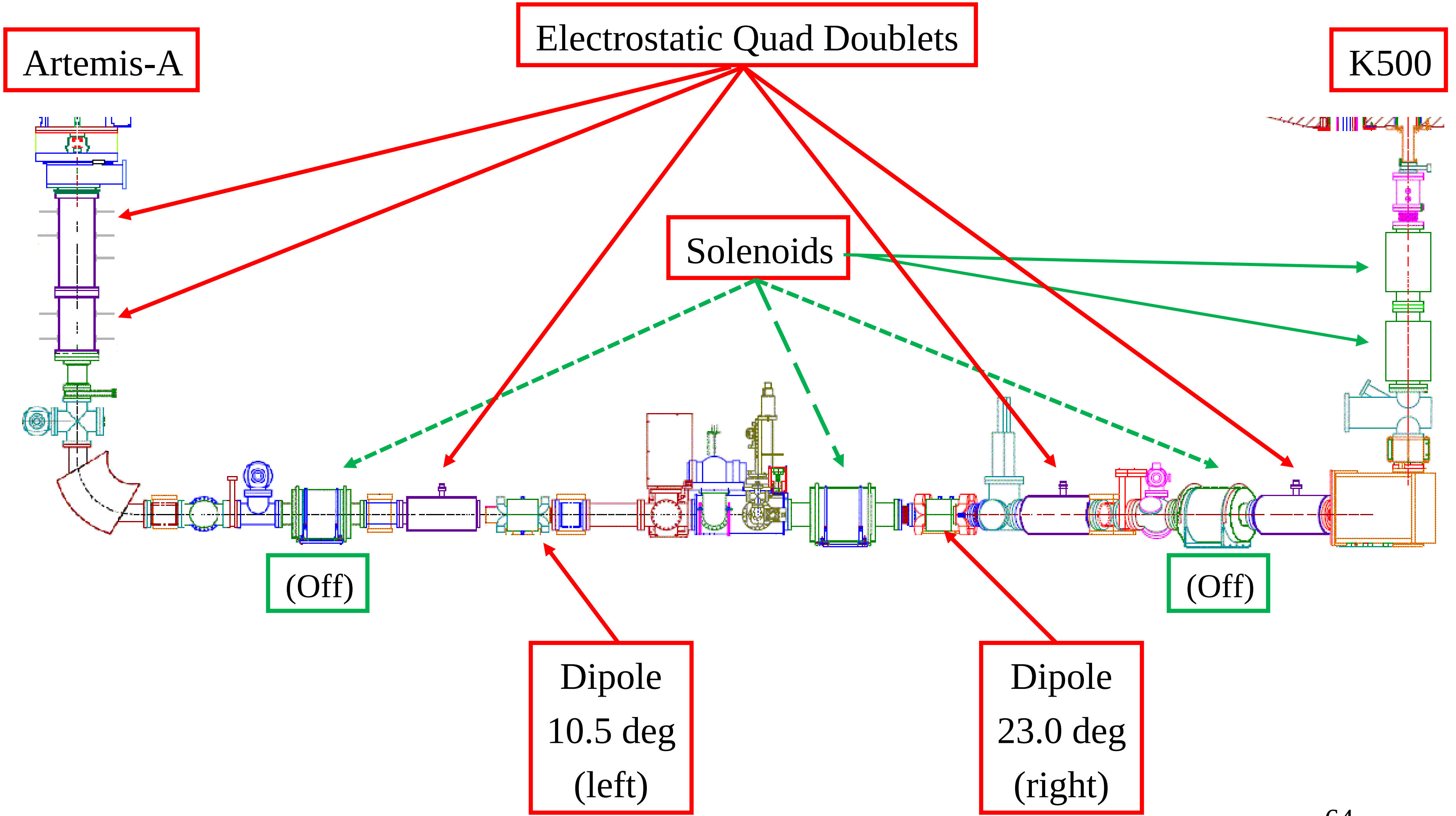
(The only such damage noted in the 2007-2010 time period and did not interrupt Beam delivery)



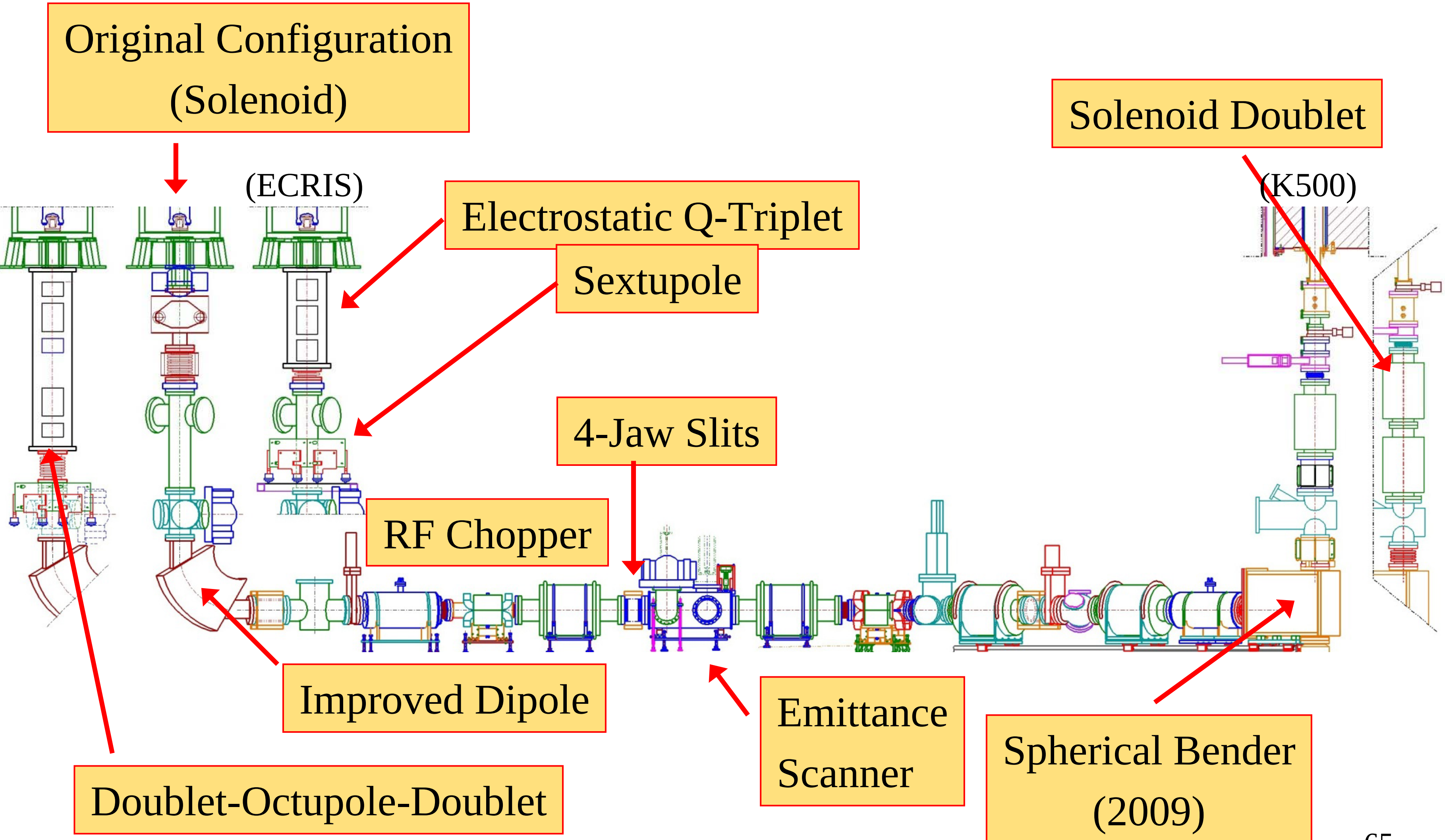
ECRIS Beam Characteristics

1) **Transverse Structure**
2) **Large 2nd Order Aberrations (Triangle)**
3) **Strong Phase space cross-coupling (beam is correlated)**
4) **Focusing morphs Triangle into Star**
5) **Under some conditions, a fractal nature (round cut can redevelop into a triangle-star)**

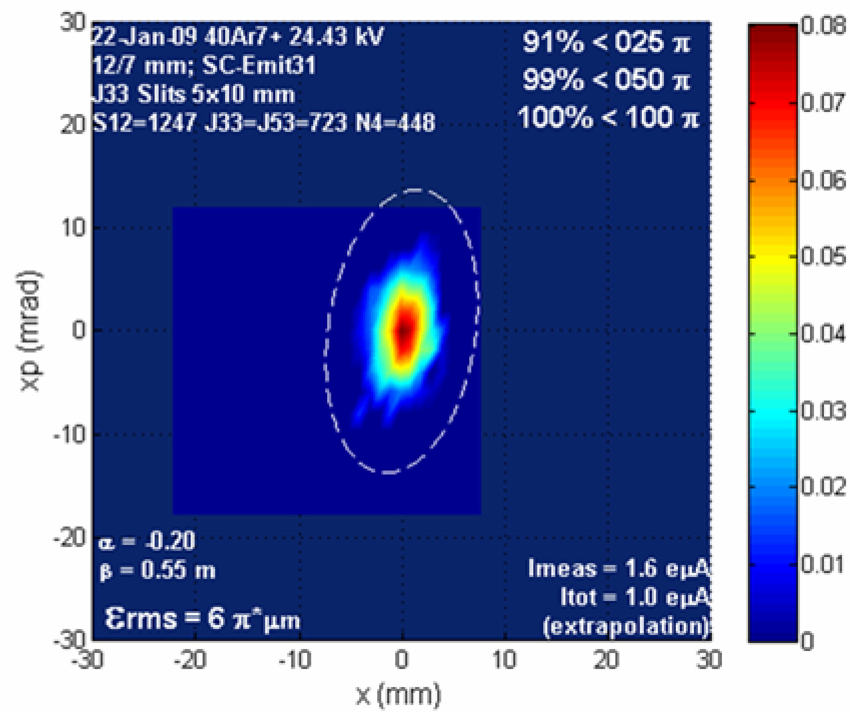
Optical Elements

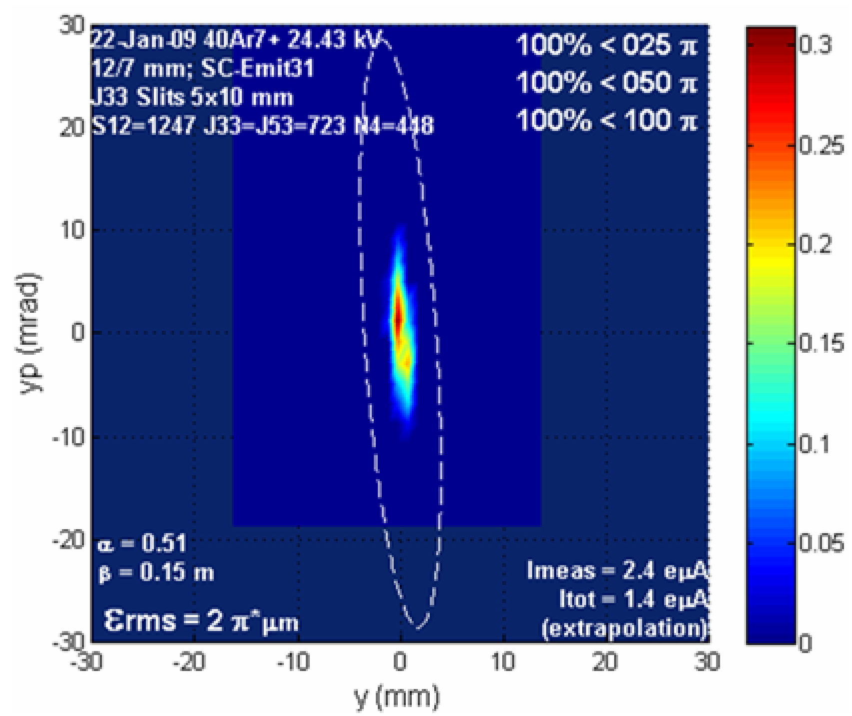


Injection Line (~16.5 m) to K500

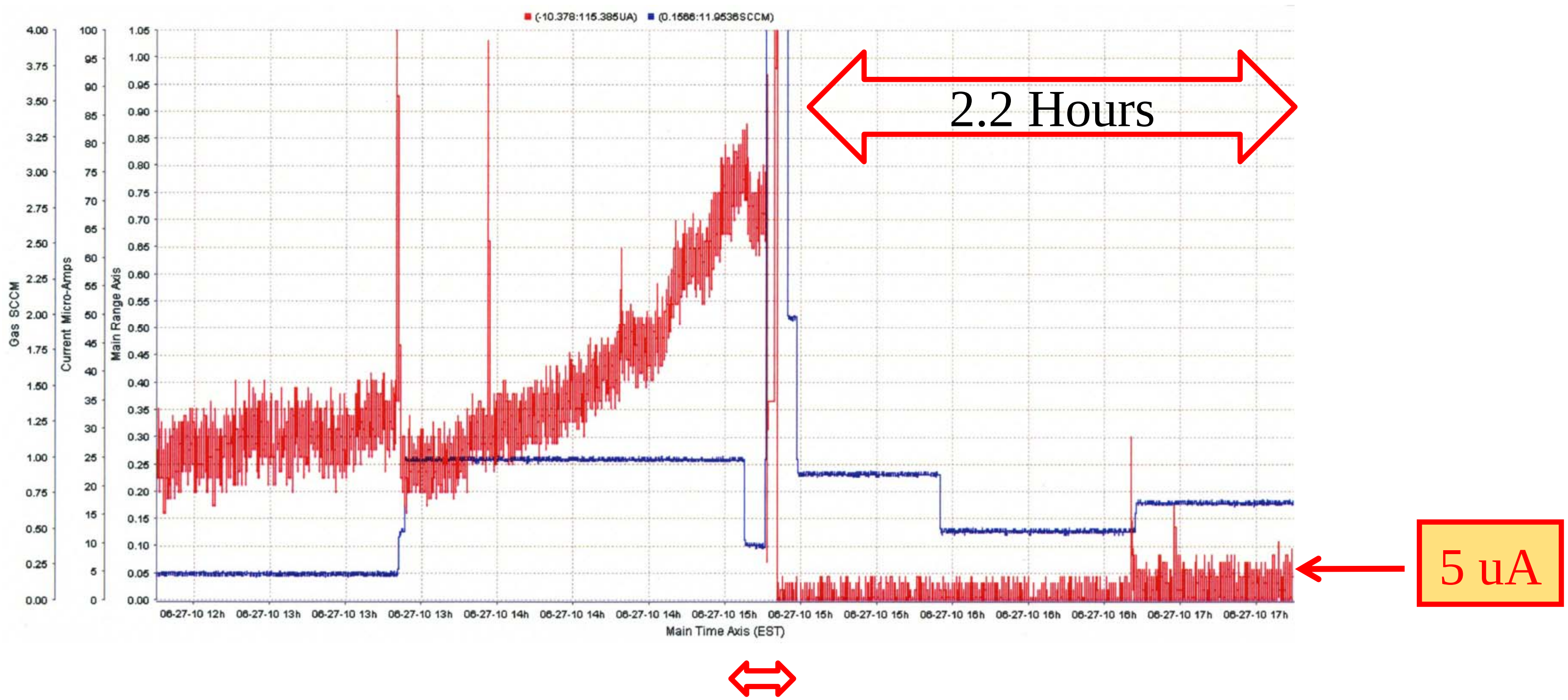


Emittance for 100% Extraction Example





Key #1: O_2 Gas Flow during Operation



Beam Time Lost = 20 minutes