Radiation Effects Studies with Ion Photon Emission Microscopy

SAND2009-5743C

19th Ion Beam Analysis IBA

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- **Outline**
  - The problems facing Radiation Effects Microscopy
  - Motivation for performing REM on Cyclotrons
  - Why the Ion Photon Emission Microscope is necessary
  - Experience using the IPEM (Tabletop, Tandem, Cyclotron)
  - Future Directions

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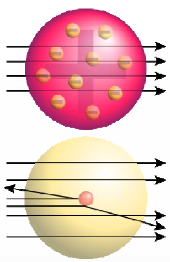
The field of IBA spans from:

Basic Physics to Applications

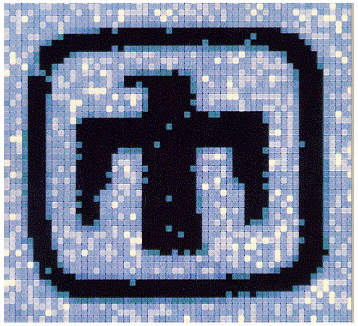
Rutherford Backscattering Spectrometry



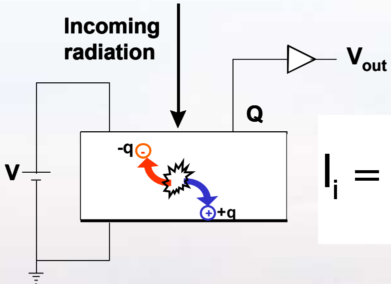
$E_1 = k * E_0$

$$k = \left(\frac{m_1 \cos\theta_1 \pm \sqrt{m_2^2 - m_1^2 (\sin\theta_1)^2}}{m_1 + m_2} \right)^2$$

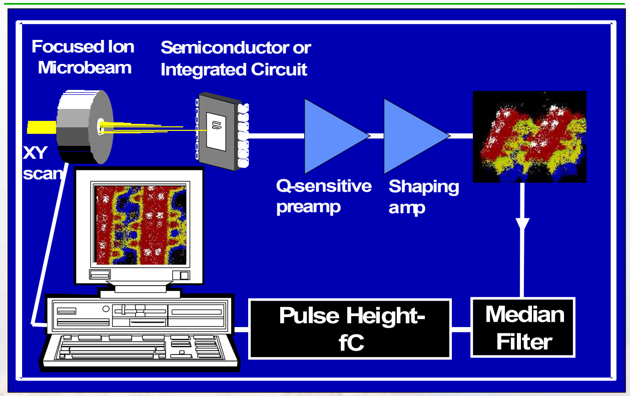
$$\frac{d\omega}{d\Omega} = \left(\frac{Z_1 Z_2 e^2}{4E_0} \right)^2 \frac{1}{(\sin\theta/2)^4}$$



Radiation Effects Microscopy



$$I_i = -q \cdot v \frac{\partial E(r)}{\partial V_i}$$



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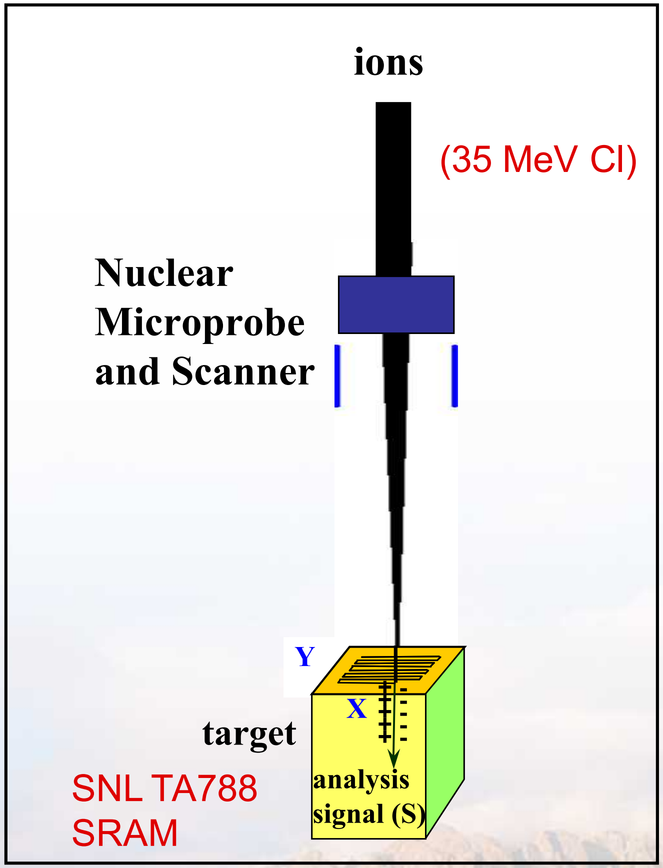
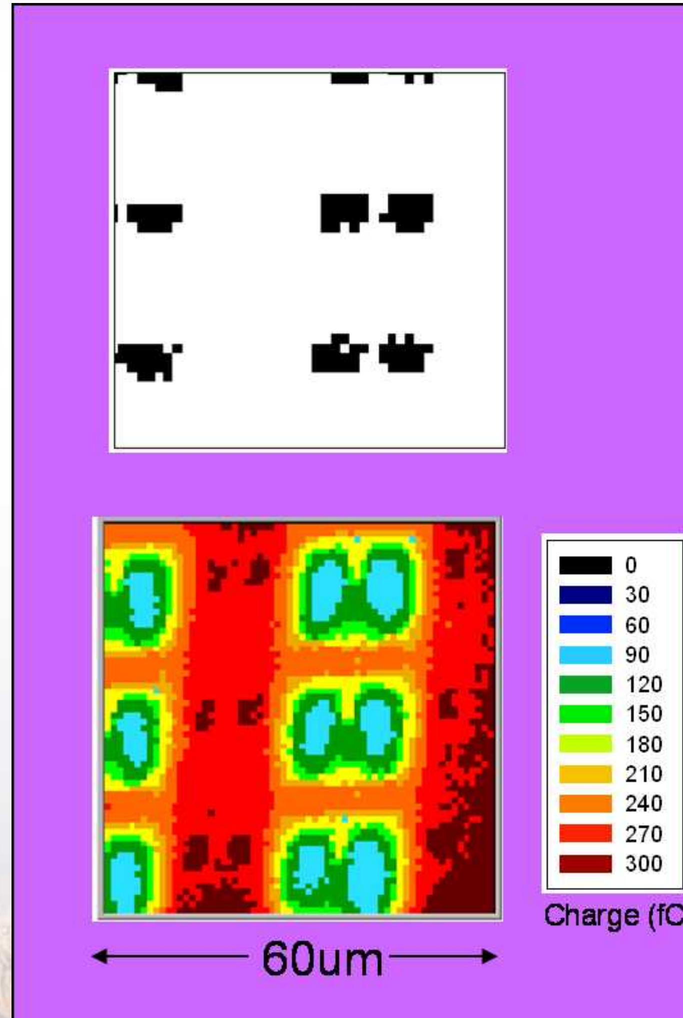
IBICC and SEU Imaging are Radiation Effects Microscopy (REM) techniques used to observe charge collection and soft upsets in ICs.



Single Event Upset Imaging

Ion Beam Induced Charge

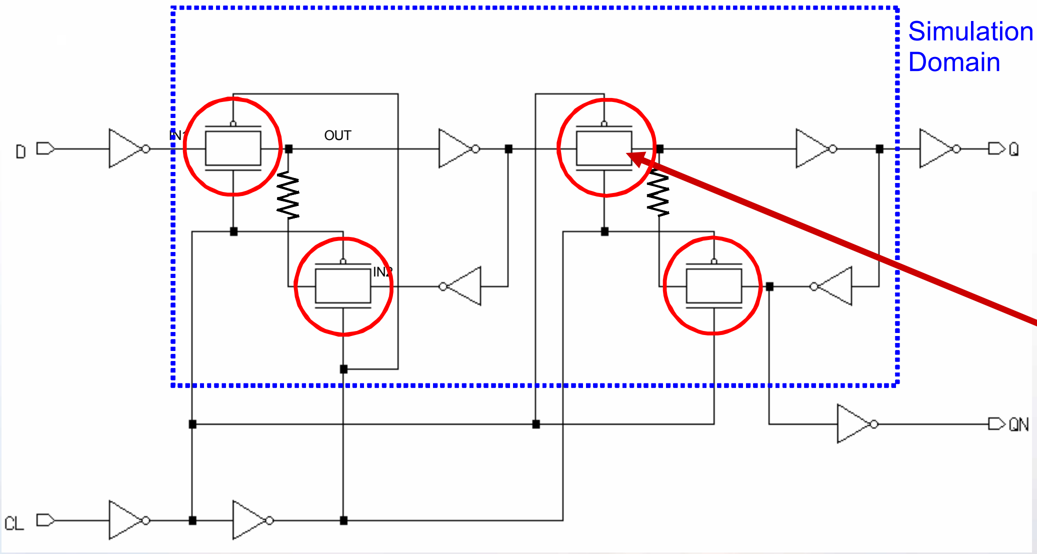
IBIC



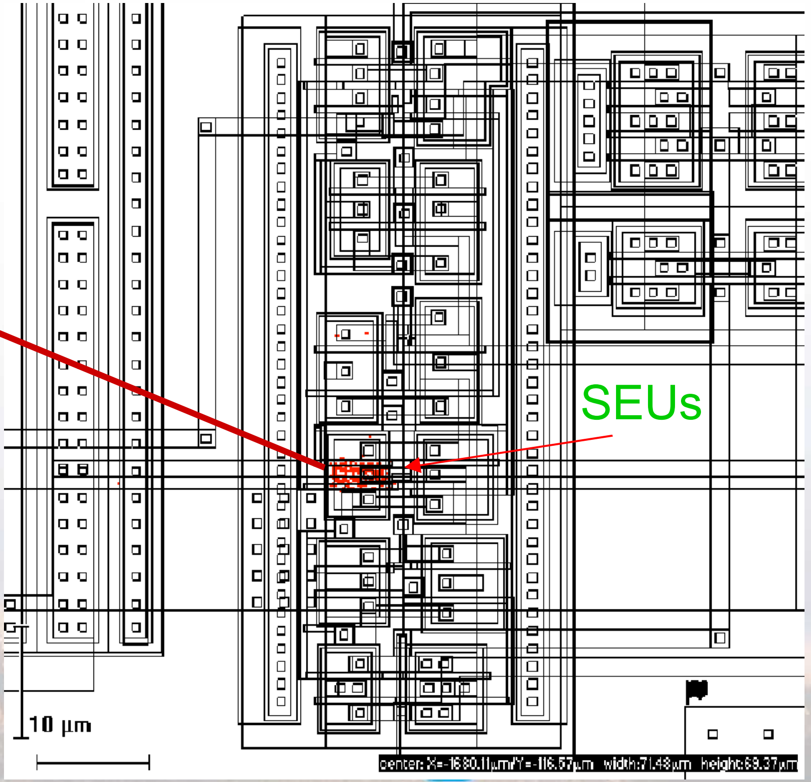
REM, and SEU imaging in particular, has proven extremely valuable in identifying individual transistors with radiation weaknesses.

In the example shown below, the transfer gates in a Latch were causing SEUs. Removal of the two resistors shown in the schematic eliminated this problem.

Latch Schematic



GDSII layout of Latch Test Structure



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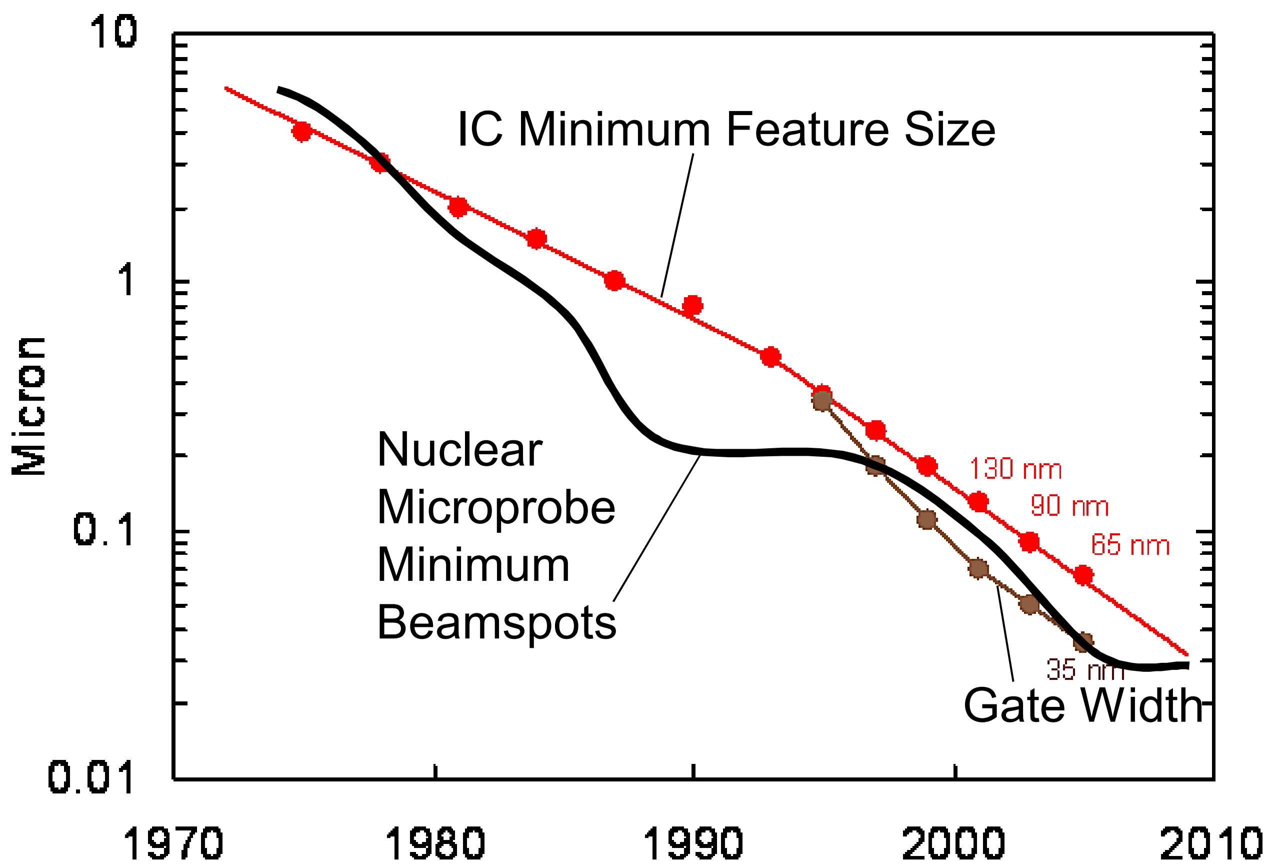
Resolution of nuclear microprobes has matched or exceeded minimum feature sizes of ICs



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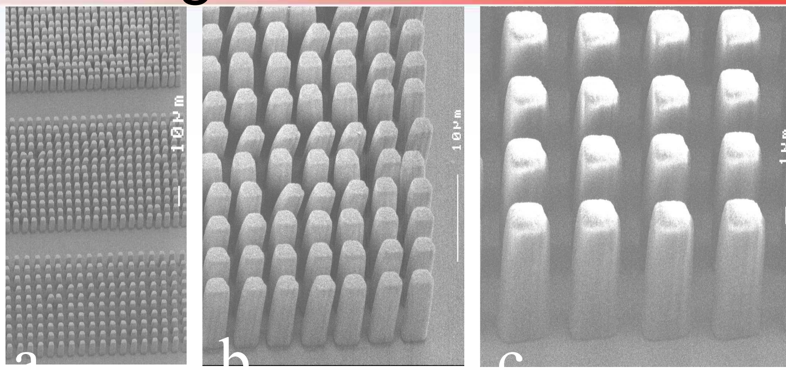
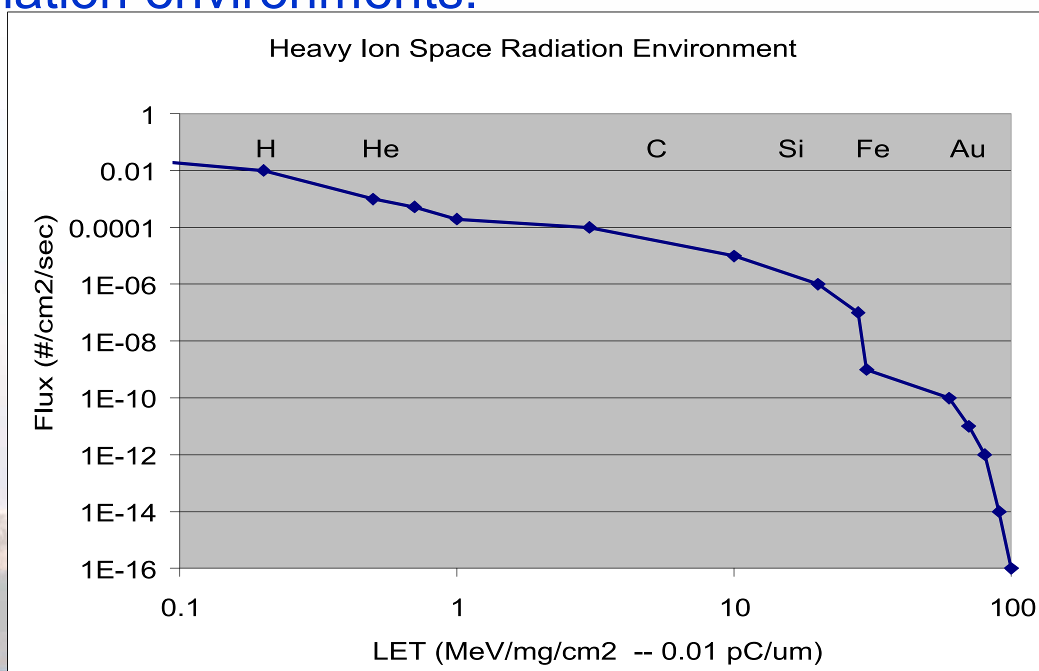
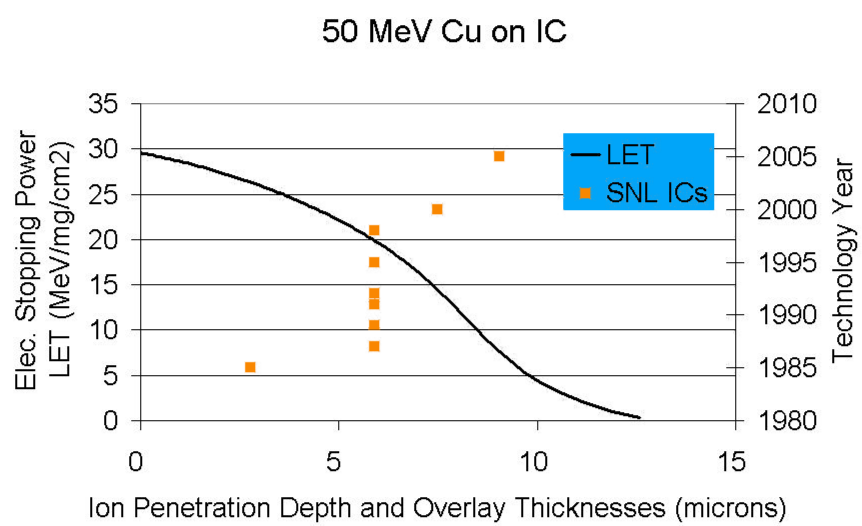
…but this high resolution of nuclear microprobes has only been demonstrated for light ions used for proton beam writing...

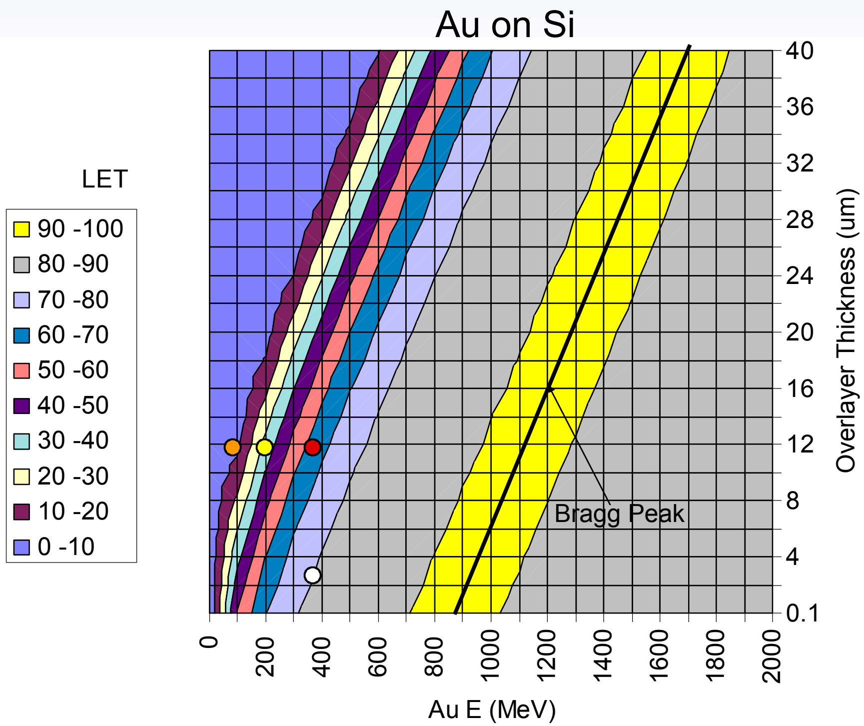


…and heavy ions are needed for REM to simulate space radiation environments.



In addition, as Minimum Feature Sizes in ICs have continued to shrink, the thickness of overlayers has increased so much that GeV energy ions are now required for REM.





- Bragg peak for Au ions occurs at 0.9 GeV with an LET of ~90 MeV/(mg/cm^2).
- SNL developed an RFQ Linac Booster for the tandem that could reach an LET of ~80.
- …but with ~ 10 µm of overlayers, over a GeV is required now to position the Bragg peak of Au into the sensitive depth.
- …and with the IC testing community preferring eXternal exposures (in air), the RFQ can only reach 40 LET in SNL's most advanced ICs.
- *So we need higher energy ions, such as those available on Cyclotrons.*

There are a lot of Cyclotrons

Cyclotrons, Individual Design

ID	Country	Institution	Machine name
C01	Belgium	UCL, Centre de Recherches	CYCLONE 110
C02	Belgium	UCL, Centre de Recherches	CYCLONE 44
C03	Canada	TRIUMF	TRIUMF Cyclotron
C04	China	Institute of Modern Physics	HIRFL injector cyclotron-SFC
C05	China	Institute of Modern Physics	HIRFL main cyclotron-SSC
C06	Czech Republic	Nuclear Physics Institute	U-120M
C07	Finland	University of Jyvaskyla,	K130 cyclotron
C08	France	cnrs	cyclotron orleans
C09	France	GANIL	C01
C10	France	GANIL	C02
C11	France	GANIL	SSC1
C12	France	GANIL	SSC2
C13	France	GANIL	CIME/SPIRAL
C14	Germany	Forschungszentrum Juelich	JULIC
C15	Germany	Hahn-Meitner-Institut Berlin	ISL Berlin
C16	Germany	ZAG Zyklotron AG	Karlsruher Compakt Anlage,
C17	India	VARIABLE ENERGY	VARIABLE ENERGY
C18	Italy	Istituto Nazionale di Fisica	LNS Superconducting
C19	Japan	CYRIC : Cyclotron and	CYRIC AVF Cyclotron
C20	Japan	Japan Atomic Energy	JAERI AVF Cyclotron
C21	Japan	Research Center for Nuclear	RCNP AVF Cyclotron
C22	Japan	Research Center for Nuclear	RCNP Ring Cyclotron
C23	Japan	RIKEN	RIKEN AVF CYCLOTRON
C24	Japan	RIKEN	RIKEN RING CYCLOTRON
C25	Kazakhstan	Institute of Nuclear Physics	Kazakhstan Isochronous
C26	Korea	Korea Institute of	KIRAMS-13
C27	Netherlands	Kernfysisch Versneller	AGOR
C28	Poland	A.Soltan Institute for Nuclear	C-30
C29	Poland	Warsaw University, Heavy	U-200P
C30	Russia	FLNR JINR	U-200
C31	Russia	FLNR JINR	U-400M
C32	Russia	FLNR JINR	U-400
C33	Russia	FLNR JINR	IC-100
C34	Russia	Petersburg Nuclear Physics	Gatchina Isochronous
C35	Russia	SINP MSU	R-7 (120- cm cyclotron)
C36	Serbia and Montenegro	Laboratory of Physics, Vinca	VINCY Cyclotron
C37	South Africa	iThemba LABS	iThemba LABS Injector
C38	South Africa	iThemba LABS	iThemba LABS Injector
C39	South Africa	iThemba LABS	iThemba LABS Separated-
C40	Sweden	The Svedberg Laboratory	Gustaf Werner Cyclotron
C41	Switzerland	Paul Scherrer Institute	PSI Philips Cyclotron
C42	Switzerland	Paul Scherrer Institute	PSI Injector 2 Cyclotron
C43	Switzerland	Paul Scherrer Institute	PSI 590 MeV Ring Cyclotron
C44	Taiwan	Institute of Nuclear Research	TR30/15 Cyclotron
C45	USA	Indiana University	Indiana University Cyclotron
C46	USA	Karmanos Cancer Institute	Harper Hospital /
C47	USA	Lawrence Berkeley National	88-Inch Cyclotron
C48	USA	Michigan State University	K500
C49	USA	Michigan State University	K1200
C50	USA	Oak Ridge National	Oak Ridge Isochronous
C51	USA	Texas A&M University	Texas A&M K500 Cyclotron

Commercial Cyclotrons, Manufacturers

ID	Country	Institution	Machine name
CM1	Belgium	Ion Beam Applications	Cyclone 14+
CM2	Belgium	Ion Beam Applications	C14 Self-Extraction
CM3	Belgium	Ion Beam Applications	C235
CM4	Belgium	Ion Beam Applications (IBA)	Cyclone 10/5
CM5	Belgium	Ion Beam Applications (IBA)	IBA C10 Cyclotron
CM6	Belgium	Ion Beam Applications (IBA)	Cyclone 18/9
CM7	Belgium	Ion Beam Applications (IBA)	Cyclone 30
CM8	Japan	Sumitomo Heavy Industries,	370V
CM9	Japan	Sumitomo Heavy Industries,	HM12
CM10	Japan	Sumitomo Heavy Industries,	HM18
CM11	Japan	Sumitomo Heavy Industries,	930
CM12	Japan	Sumitomo Heavy Industries,	C235

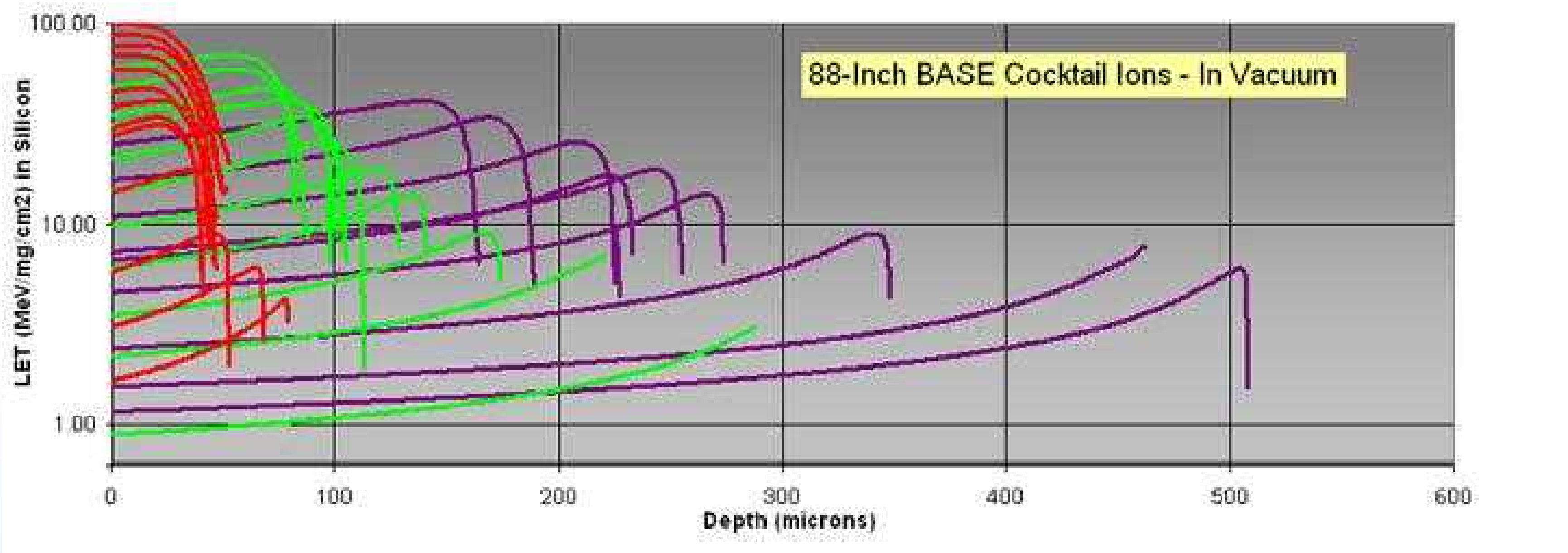
Commercial Cyclotrons, Users

ID	Country	Institution	Machine name
CU01	Australia	ANSTO	CYCLONE30
CU03	Brazil	Energetic and Nuclear	CYCLONE-30
CU04	Brazil	Instituto de Pesquisas	CV-28 Cyclotron
CU05	Canada	Hamilton Health Sciences	Radio Isotope Delivery
CU06	Canada	TRIUMF	TR13
CU07	Germany	Forschungszentrum Juelich,	CV 28
CU08	Germany	Forschungszentrum	CYCLONE 18/9
CU09	Hungary	Institute of Nuclear Research	MGC-20
CU10	Italy	European Commission -	Scanditronix MC40
CU11	Japan	Daiichi Radioisotope	Cyclone 30
CU12	Japan	Daiichi Radioisotope	MC-40
CU13	Japan	NIRS: National Institute of	NIRS-Chiba Isochronous
CU14	Japan	NIRS: National Institute of	HM-18
CU15	Japan	S.H.I. Examination &	HM-18
CU16	Korea	Korea Institute of	CYCLONE30
CU17	Korea	Korea Institute of	MC50
CU18	Netherlands	PET-Center Groningen	Scanditronix MC-17F
CU19	Netherlands	Technische Universiteit	TU/e cyclotron, IBA Cyclone
CU20	Norway	Department of Physics,	Oslo Cyclotron
CU22	United Kingdom	University of Cambridge	GE PETtrace
CU23	United Kingdom	University of Cambridge	Cyclone-3
CU24	USA	Johns Hopkins University	General Electric PETtrace
CU25	USA	National Institutes of Health	NIH PetTrace
CU26	USA	National Institutes of Health	NIH JSW-1710
CU27	USA	National Institutes of Health	NIH - CS30
CU28	USA	University of Washington	Clinical Cyclotron
CU29	USA	University of Wisconsin	UW Medical Physics CTI
CU30	Sweden	PET Center, Uppsala	MC 17 Cyclotron

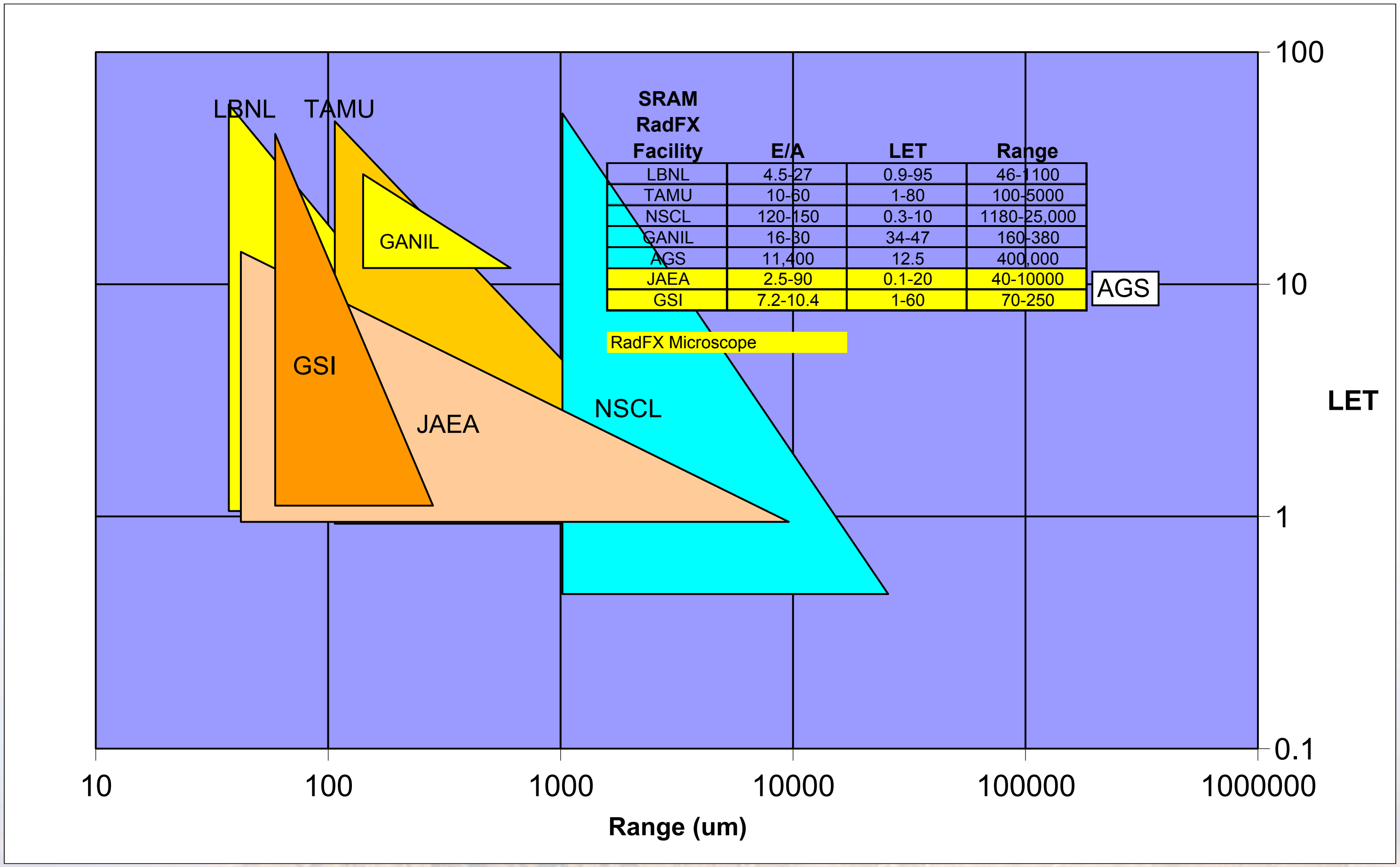
FM Cyclotrons

ID	Country	Institution	Machine name
FM1	France	Institut Curie - Centre de	Synchrocyclotron 200 MeV
FM2	Russia	PNPI RAS	Synchrocyclotron on 1 GeV
FM3	Russia	JOINT INSTITUTE for	PHASOTRON

…but only a few are used for RadFX testing like the 88” Cyclotron at LBNL



…and of those, only 2 have focused beam Radiation Effects Microscopes (+GSI UNILAC)



SRAM RadFX Facility	E/A	LET	Range
LBNL	4.5-27	0.9-95	46-1100
TAMU	10-60	1-80	100-5000
NSCL	120-150	0.3-10	1180-25,000
GANIL	16-30	34-47	160-380
AGS	11,400	12.5	400,000
JAEA	2.5-90	0.1-20	40-10000
GSI	7.2-10.4	1-60	70-250

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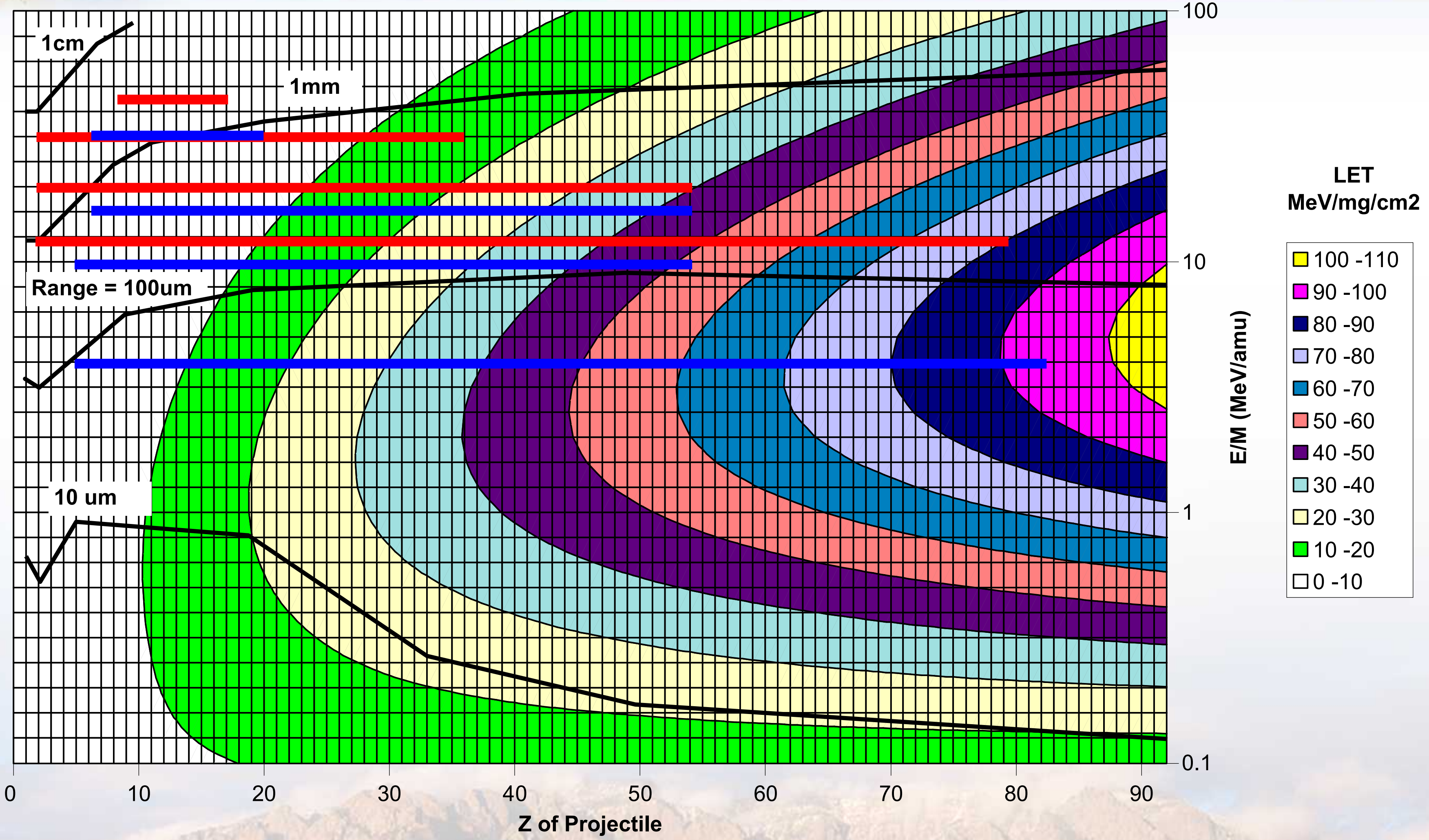
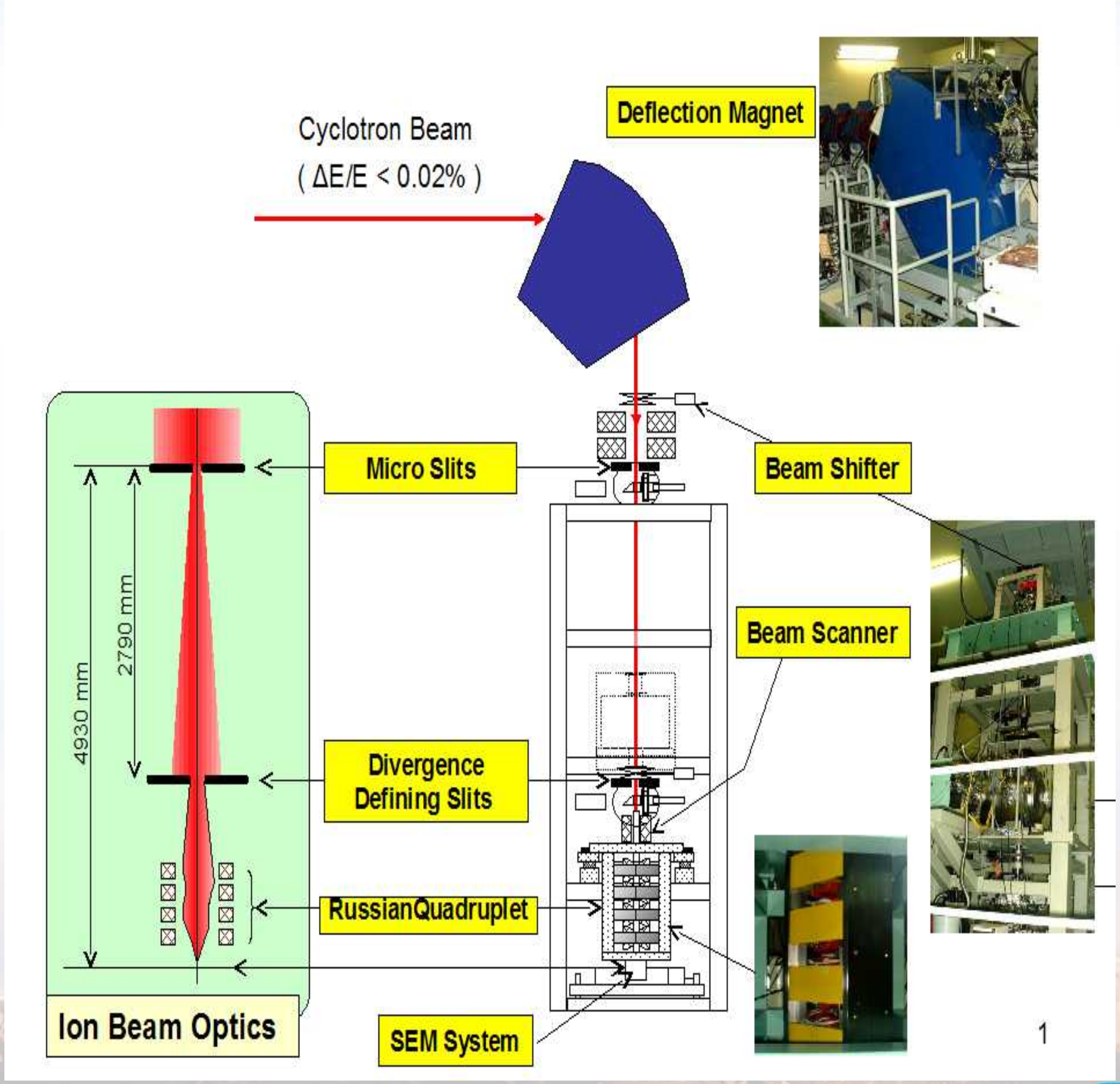
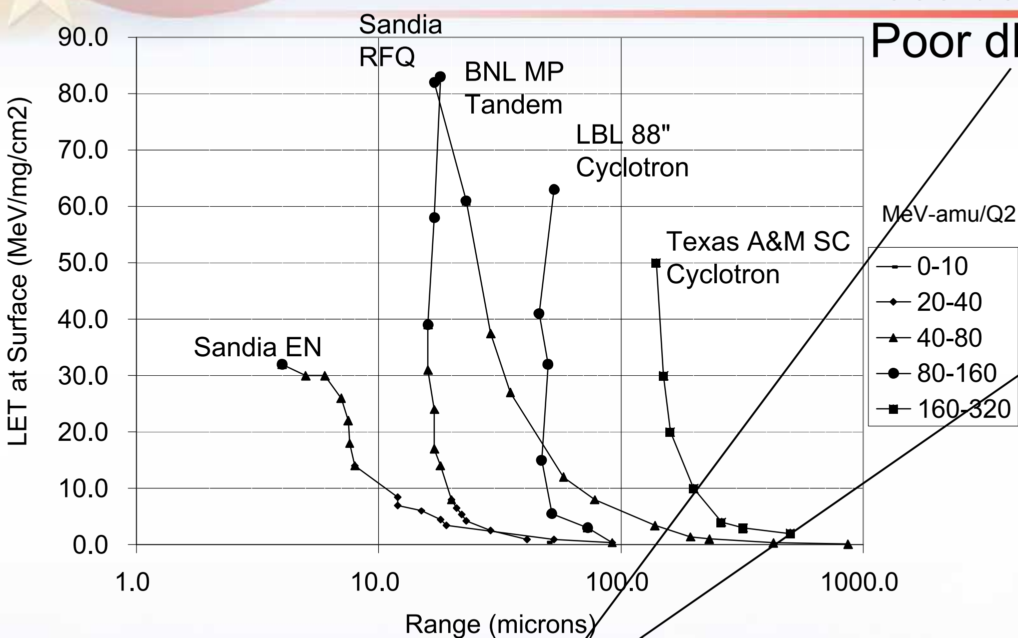
The LET and Range capabilities of the LBNL K150 and TAMU K500 Cyclotrons are ideal for REM.

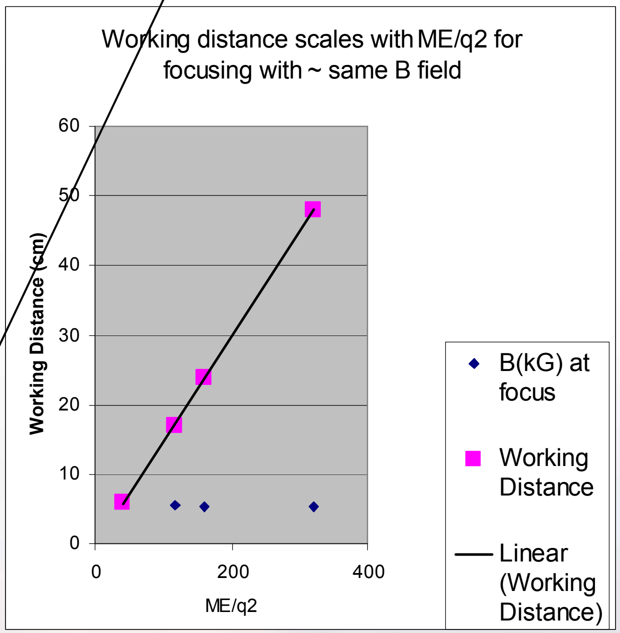


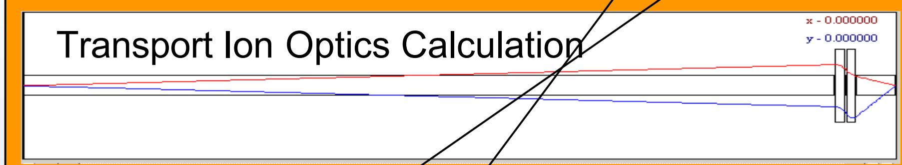
So, why not focus a beam on the Cyclotron at Berkeley, like they do at JAEA and GSI?



Answer: Increased magnetic rigidity =>
longer working distance =>
less demagnification of lens system =>
Poor dE/E=> smaller object slits =>
less beam on target
increase of slit scattering







x (um)	4.5
x' (mrad)	0.05
y (um)	15
y' (mrad)	0.05
dE/E	0.003

vertical: 22¼ mm mrad
horizontal: 16¼ mm mrad
longitudinal: .3 x 30 deg (¢) E/E)%xdeg RF
ions / energy(MeV/N)/current(pps)/power(w)
136Xe28+ 6x10e11 ions/s

brightness= 1704545455 ions/mm2mrad2

1um with chrom
current 288 ions/s

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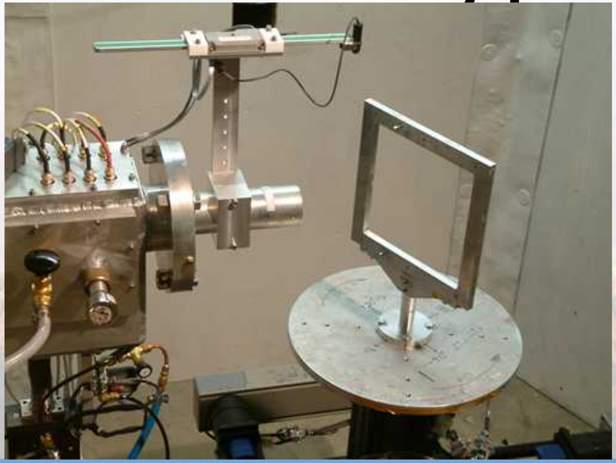
So let's review the problems

- **REM of modern ICs requires high energy heavy ions focused to extremely small spots because:**
  - Minimum feature sizes are << 1 um
  - Overlayers are typically > 10 um
- **Focused nuclear microprobes have demonstrated high enough resolution, but only for light ions.**
- **Cyclotrons produce the right ions, but hard to focus due to high ME/q^2 and poor energy resolution.**
- **… and the IC test community prefers exposing their chips in air!**



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Solution: the Ion Photon Emission Microscope or IPEM

(12) **United States Patent**
Doyle

(10) **Patent No.:** **US 6,552,338 B1**
(45) **Date of Patent:** **Apr. 22, 2003**

(54) **ION PHOTON EMISSION MICROSCOPE**

(75) Inventor: **Barney L. Doyle**, Albuquerque, NM (US)

(73) Assignee: **Sandia Corporation**, Albuquerque, NM (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 98 days.

(21) Appl. No.: **09/882,400**

(22) Filed: **Jun. 14, 2001**

(51) **Int. Cl.**[7] **G01N 23/00**; G21K 7/00
(52) **U.S. Cl.** **250/309**; 250/306; 250/308; 250/310; 356/73; 356/300; 356/326; 356/328; 356/337.1
(58) **Field of Search** 250/306, 308, 250/309, 310; 356/73, 300, 326, 328, 237.1

(56) **References Cited**

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Doyle, B.L., Walsh, D.S., Renfrow, S.N., Vizkelethy, G., Schenkel, T. and Hamza, A.V., "Nuclear Emission Microscopies," presented at the 7th Intl. Conf. on Nuclear Microprobe Tech. & Appl., Sep. 10–15, 2000.

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* cited by examiner

Primary Examiner—John R. Lee
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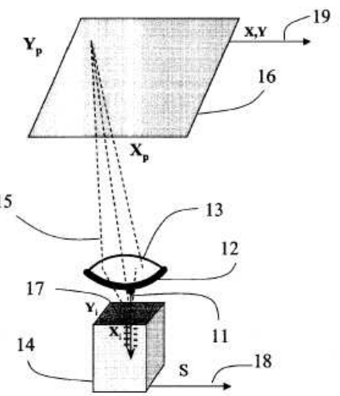
(57) **ABSTRACT**

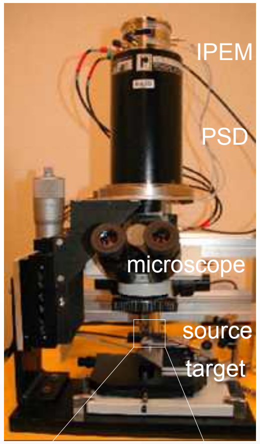
An ion beam analysis system that creates microscopic multidimensional image maps of the effects of high energy ions from an unfocussed source upon a sample by correlating the exact entry point of an ion into a sample by projection imaging of the ion-induced photons emitted at that point with a signal from a detector that measures the interaction of that ion within the sample. The emitted photons are collected in the lens system of a conventional optical microscope, and projected on the image plane of a high resolution single photon position sensitive detector. Position signals from this photon detector are then correlated in time with electrical effects, including the malfunction of digital circuits, detected within the sample that were caused by the individual ion that created these photons initially.

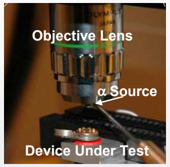
30 Claims, 2 Drawing Sheets



Ion Photon Emission Microscope - IPEM

A device that can perform nuclear-microscopy in air without focussing the ion beam.





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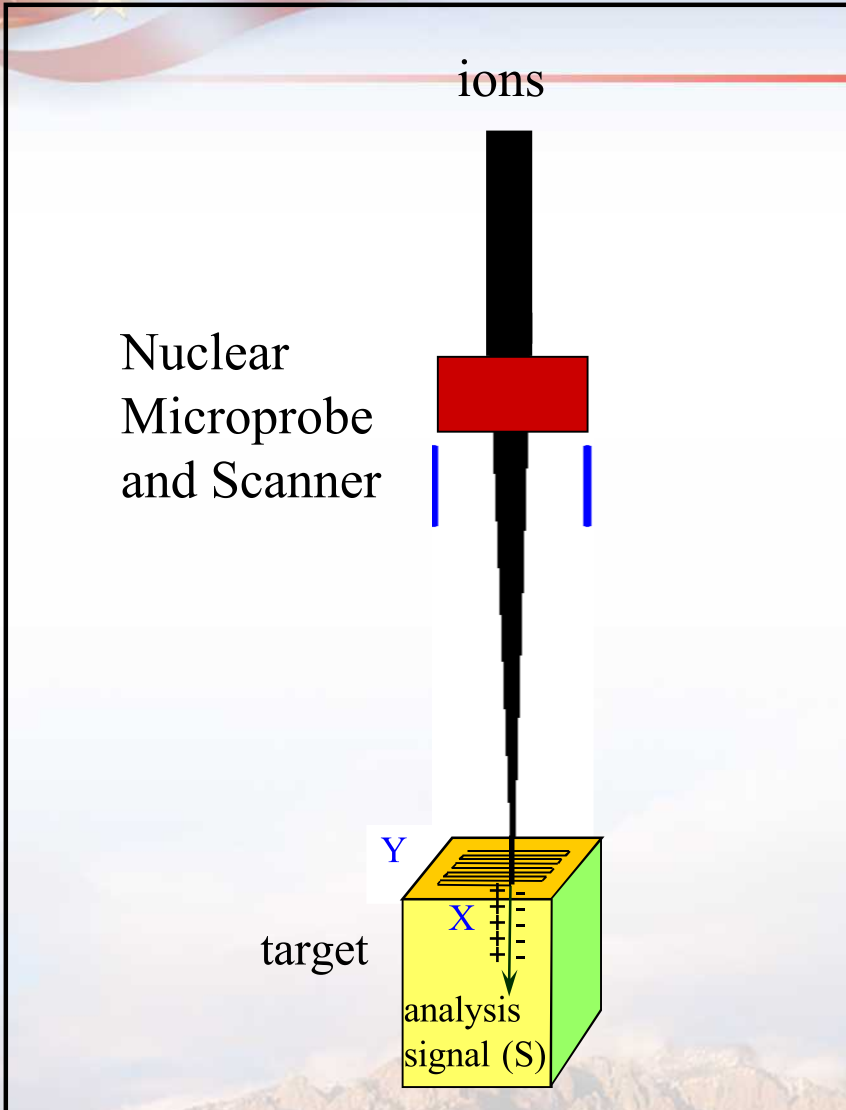
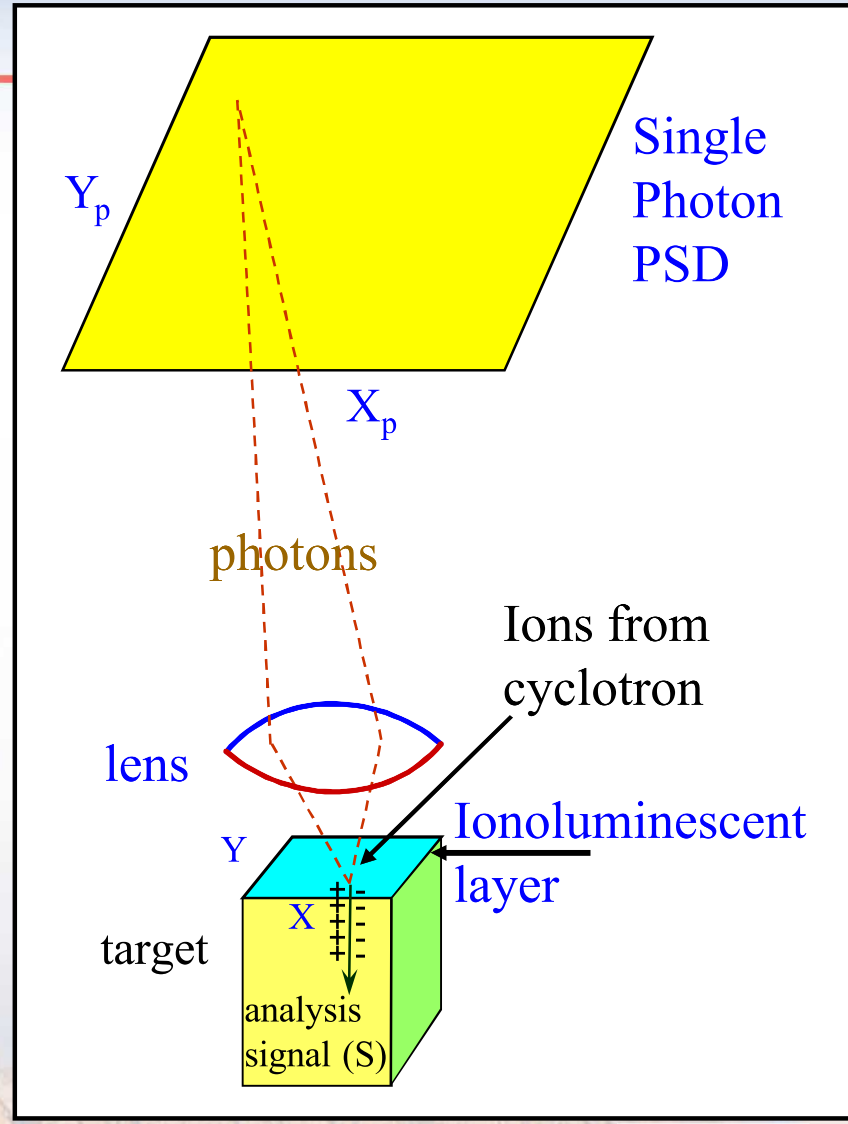
Floyd Del McDaniel

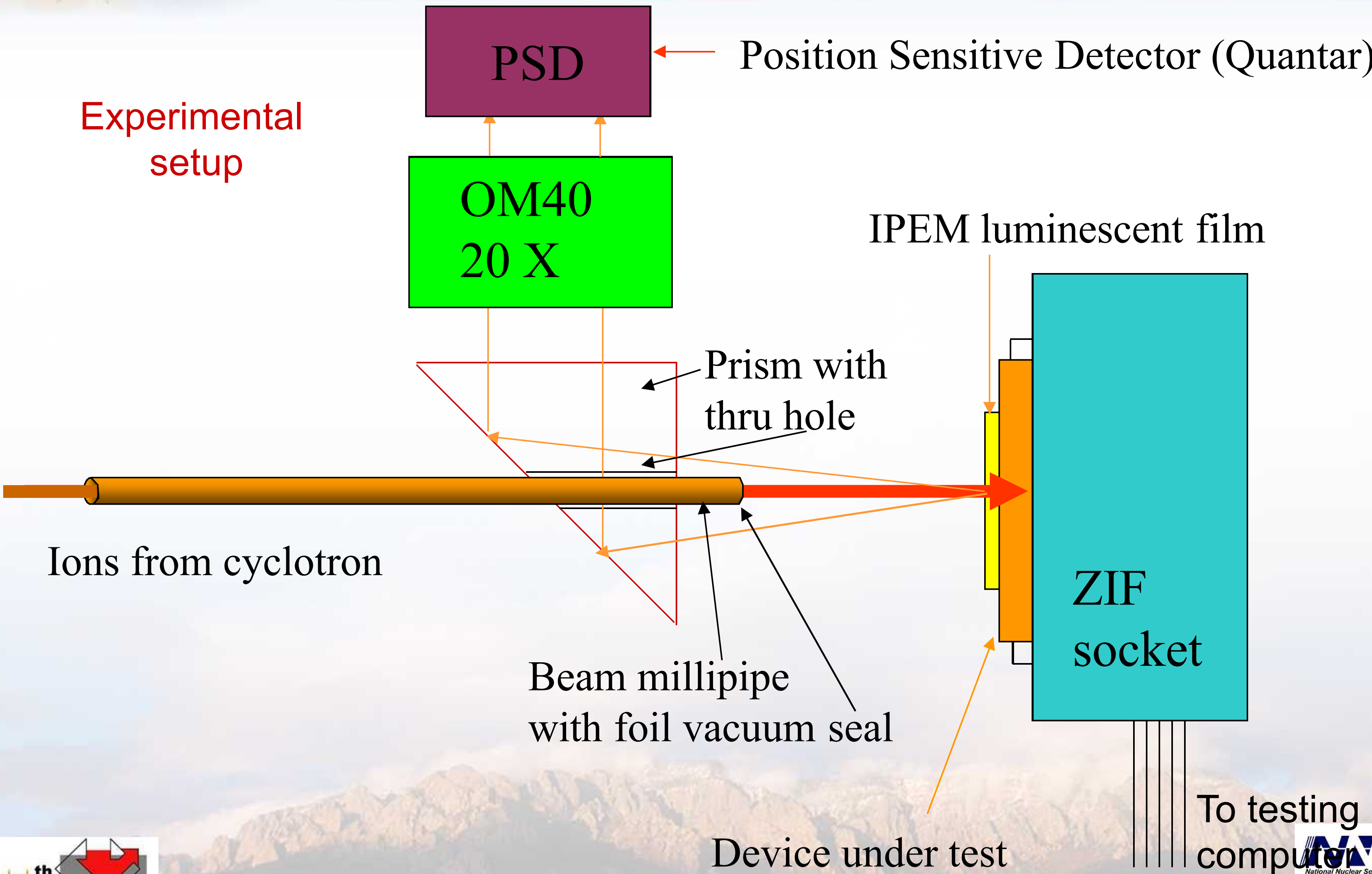
Nuclear Microprobe Analysis



Ion-Photon Emission Microscopy



The system proposed here, is to still perform IPEM in air, but using the TAMU Cyclotron instead of the alpha source.



IPEM Film Material Requirements

Emission wavelength to match detector efficiency

High Efficiency (detect at least 1 photon/ion)

Short luminescent lifetime

Easy to handle

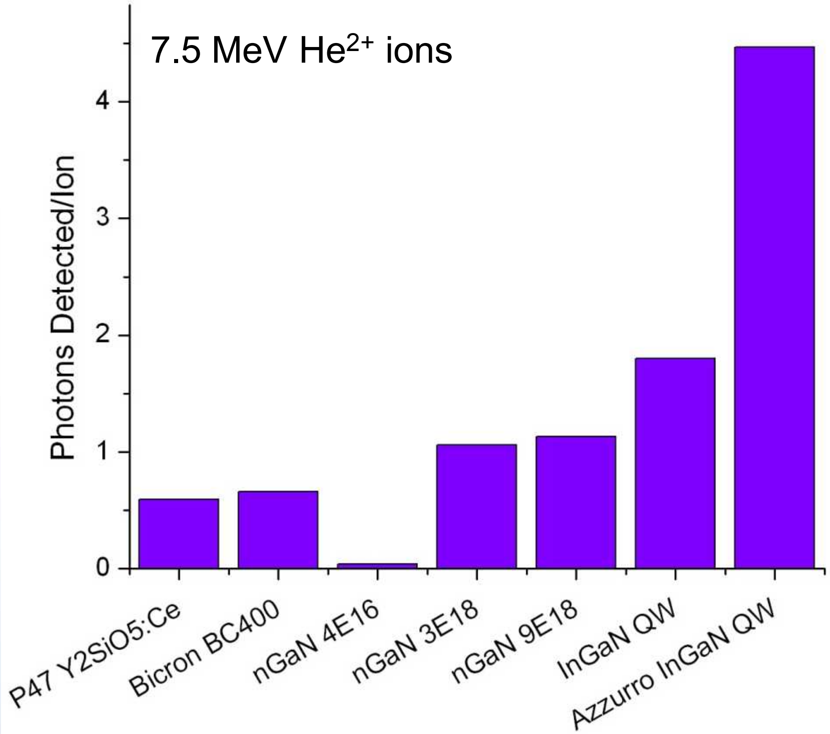
Thin single crystal or nanophosphor layer to optimize resolution

Tolerant to radiation damage, esp. at GeV energies for long periods of time

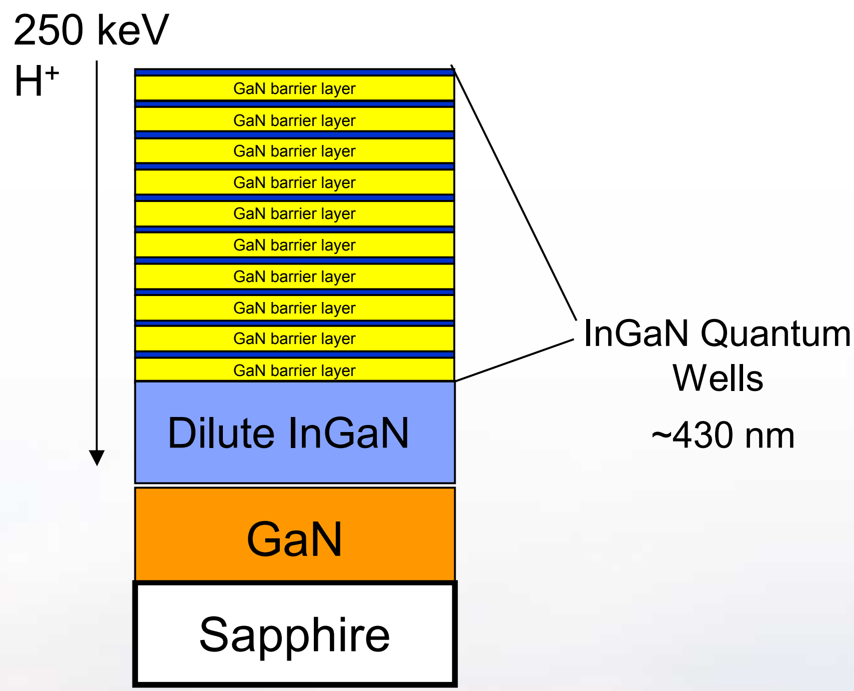
Homogeneous luminescent properties

IPEM Film Selection

Materials selection via IBIL intensity

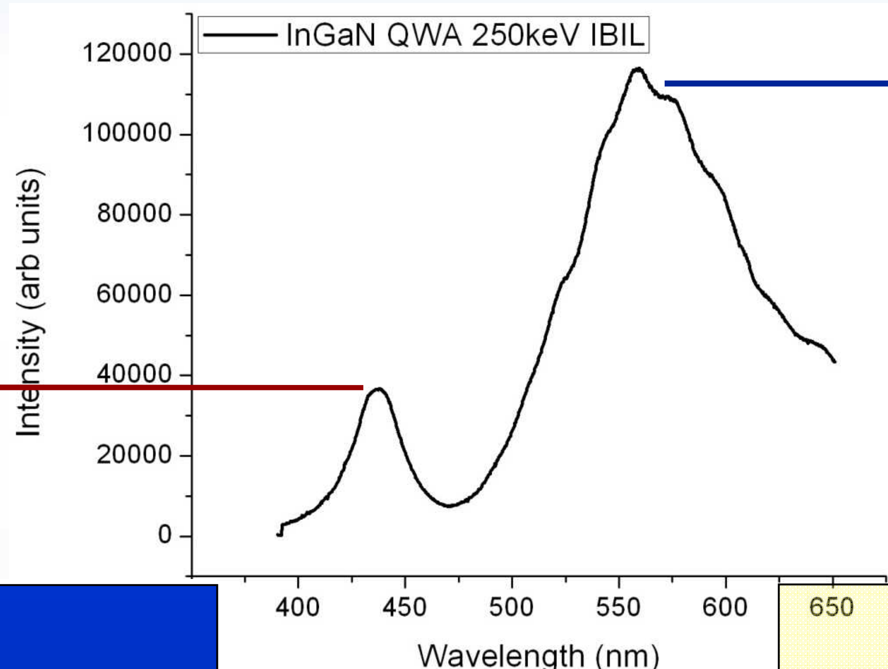


InGaN/GaN quantum well structure



- InGaN/GaN quantum wells demonstrate highest light yield (photons/ion) of materials investigated

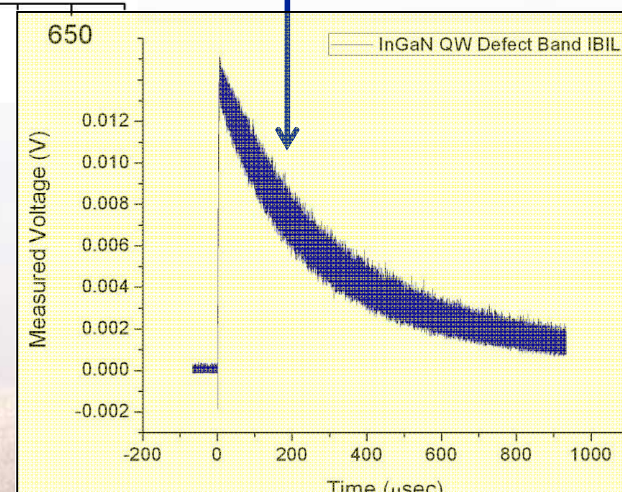
InGaN/GaN MQW Properties



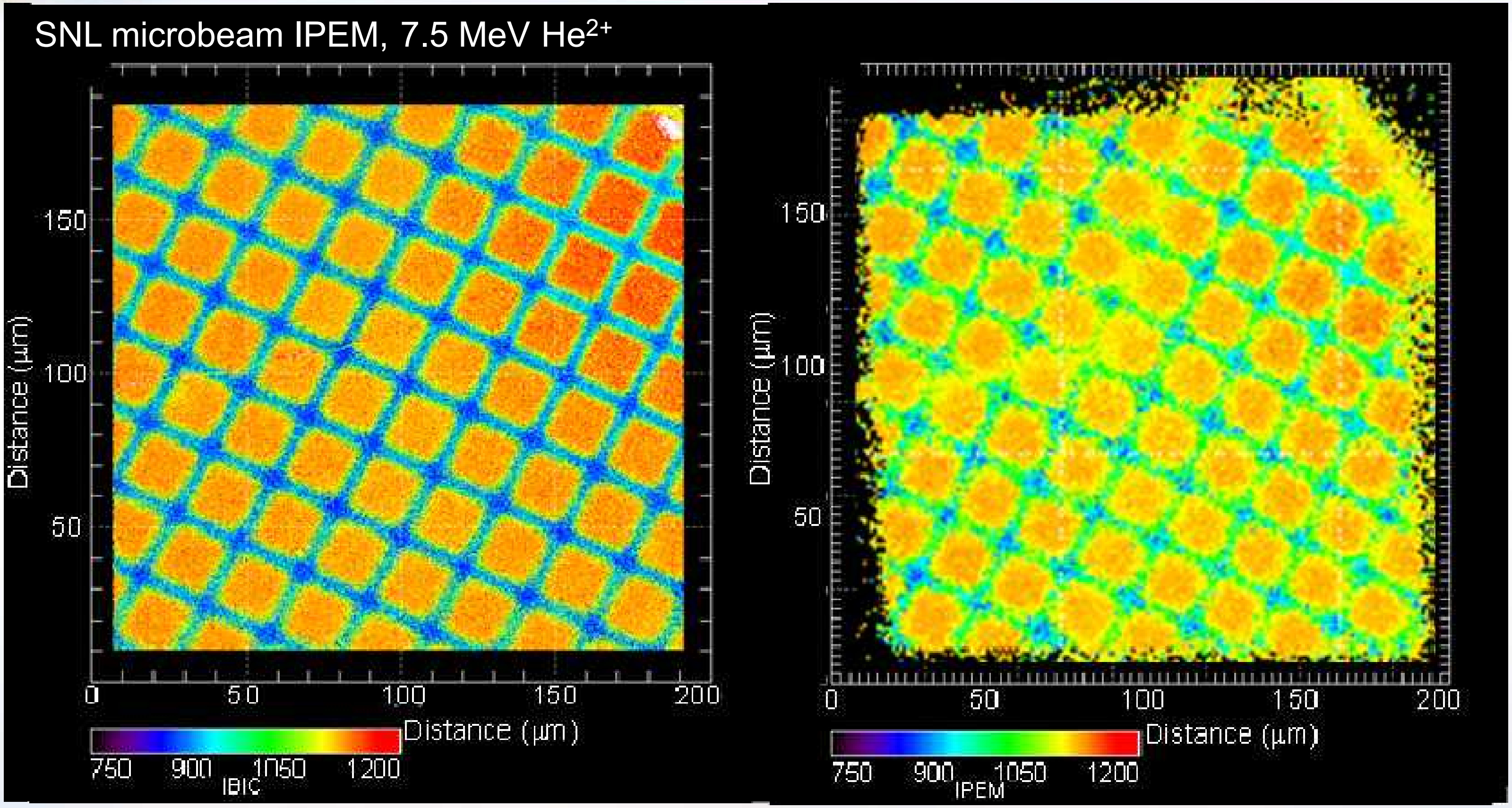
Defect band emission –long lifetime (hundreds of μs)

Bandedge emission – short lifetime (ns)

- InGaN/GaN quantum wells demonstrate two major emission bands
- Short lifetime bandedge emission (~430 nm)
- Long lifetime defect band emission (~550 nm)



Tandem IPEM Results

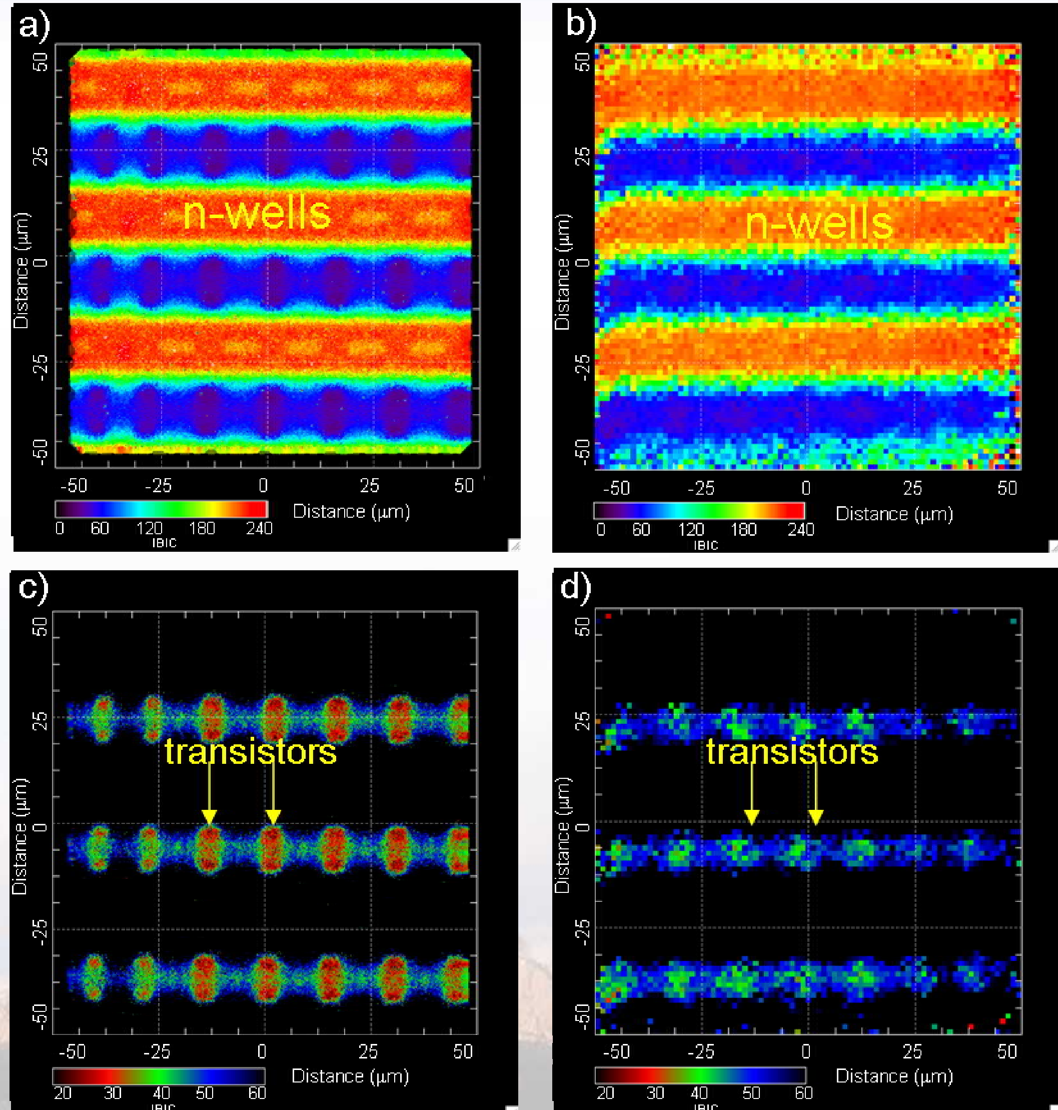


- IBIC on diode + 1000 mesh TEM grid + GaN film
- Scanned Focused Beam
- Median Filter

- IPEM IBIC median filter image taken at same time.
- Resolution ~ 2.5 microns

Tandem IPEM Results

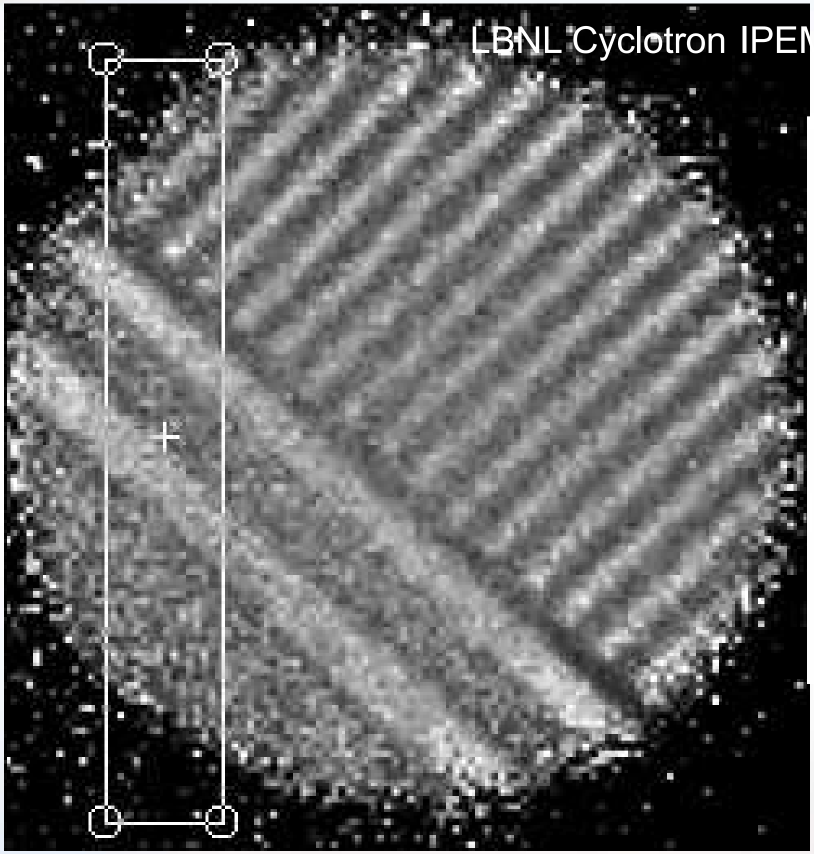
- IBIC images of TA788 from scanning microbeam of 30 MeV C^{5+} ions
- n-wells easily distinguishable – high charge collection in junctions between n-well and p-substrate
- Intensity range modified in bottom image to resolve details in p-substrate
- IBIC on device + GaN film

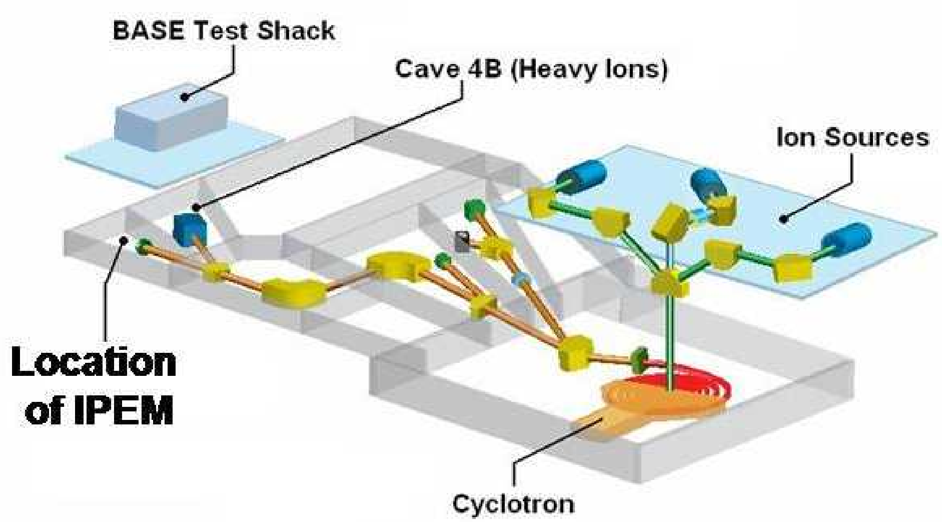


SNL microbeam IPEM, 30 MeV C^{5+}

- IPEM/IBIC image of TA788 with 5 µm GaN as luminescent film
- Can still distinguish details, but resolution not comparable to focused scanned-beam IBIC
- Intensity range modified in bottom image to resolve details in p-substrate
- IPEM/IBIC on device + GaN film

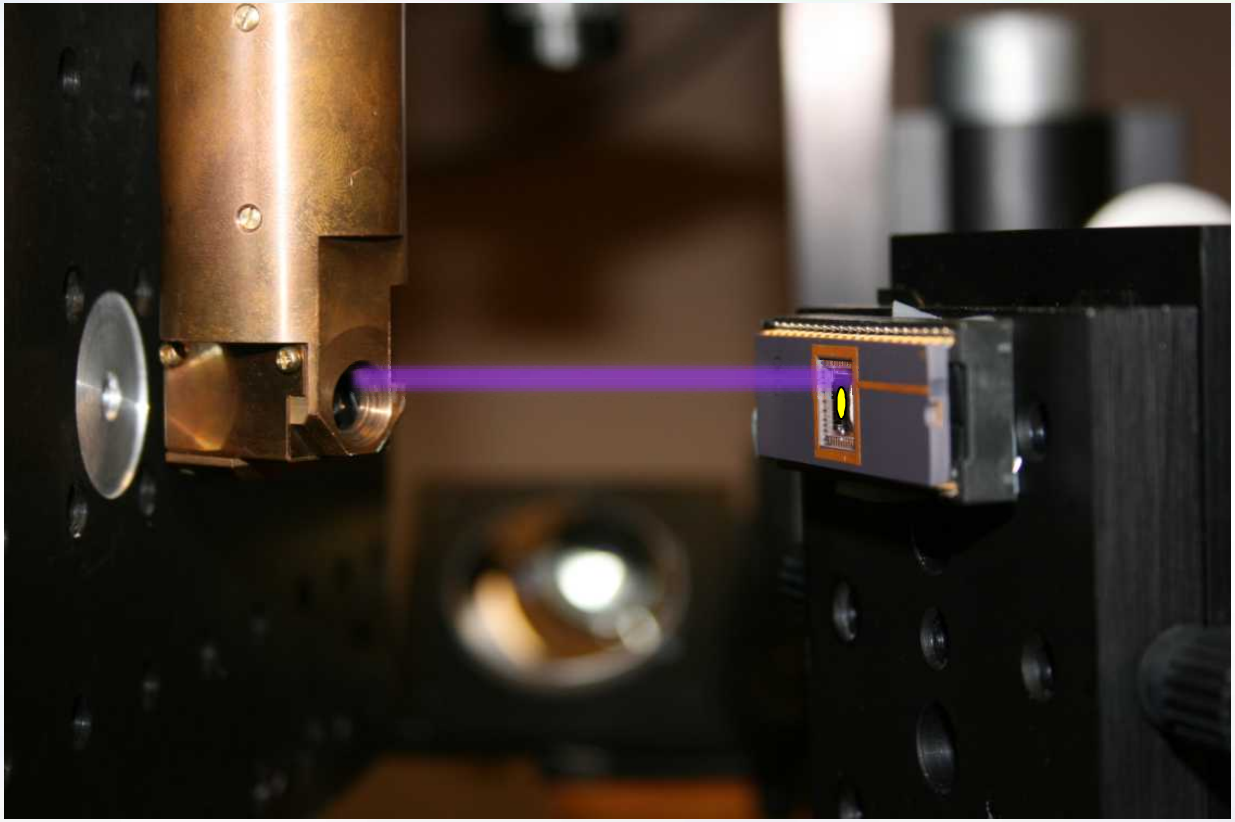
Cyclotron IPEM Results





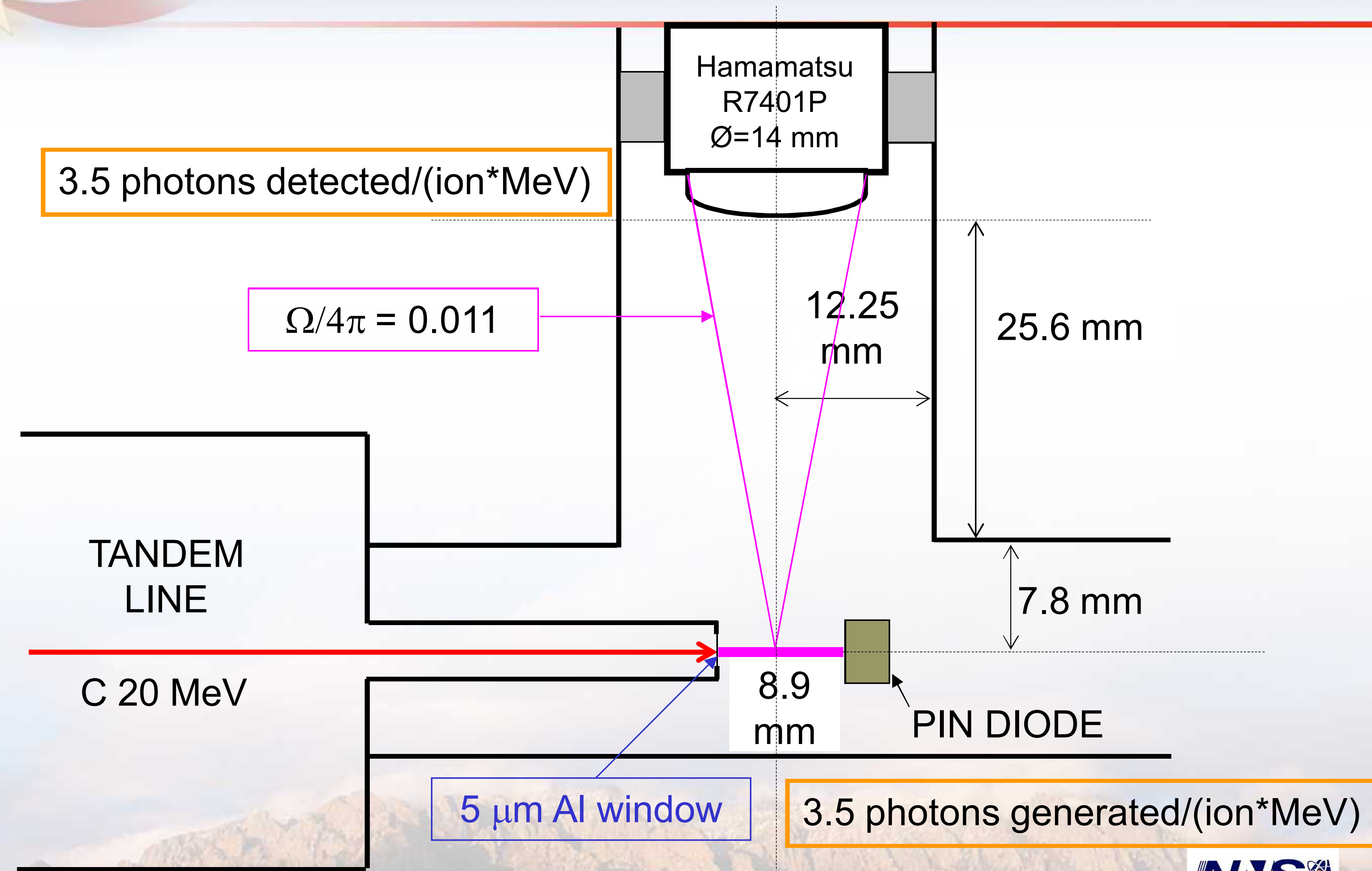
- First IPEM image obtained from LBNL cyclotron 10 MeV/amu Ne beam
- Device is a Sandia TA788 SRAM
- Fair IBIC Images obtained only for this relatively light ion.
- Higher mass ions produced poor quality IBIC images of SRAMS and TEM Grids

This led us to suspect that luminescence was occuring in the airpath between the microscope and the device.



And because this light has a shorter lifetime than the GaN IPEM film, it arrives in the IPEM detector first, and is out of focus.   The correlation between the photon's position and the ion strike point is therefore lost as is the resolution of the IPEM system.

To check this hypothesis, an experiment was performed on the tandem.

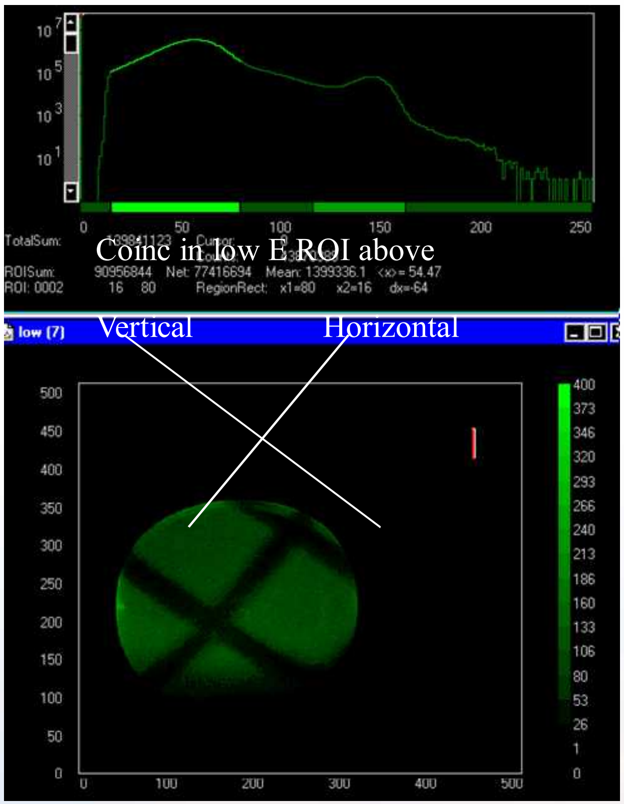


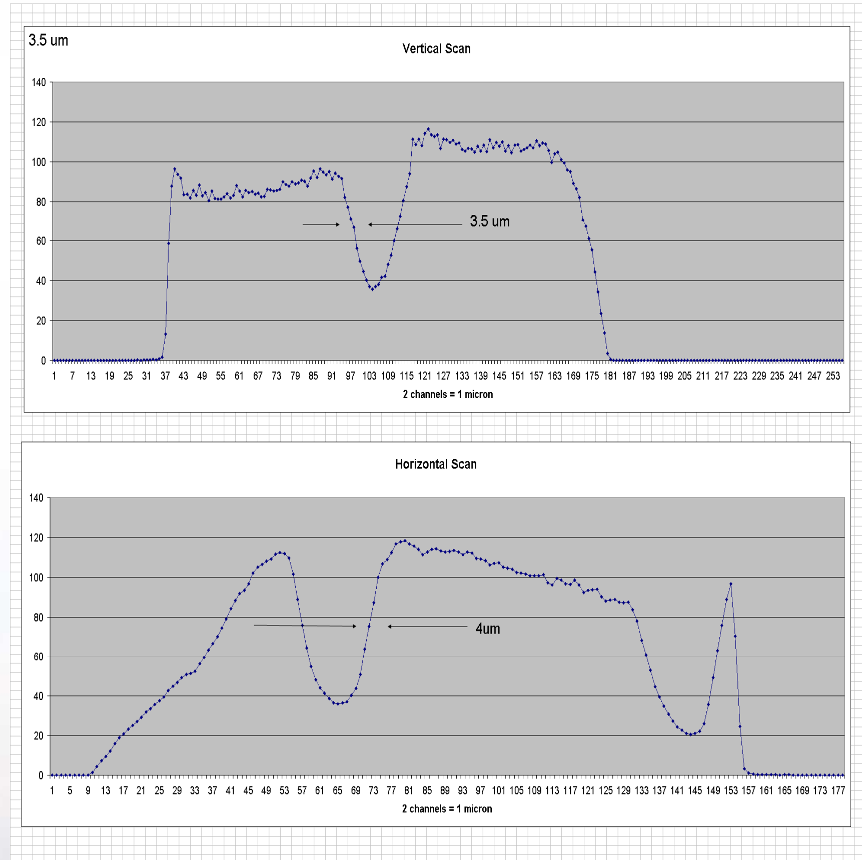
BERKELEY CYCLOTRON AIR LUMINESCENCE

ph/ion is also the probability that the position as determined by the IPEM is WRONG.

ION	E MeV	dE/dt MeVcm2/mg	density mg/cm3	dE/dx MeV/cm	Range cm	path cm	ΔEinPath MeV	ph/ion
B	108	1.00	1.25	1.25	50.00	0.60	0.75	**0.02**
O	183	2.53	1.25	3.16	38.50	0.60	1.90	**0.04**
Ne	216	3.70	1.25	4.63	30.00	0.60	2.78	**0.06**
Ar	400	11.10	1.25	13.88	21.10	0.60	8.33	**0.17**
Cu	659	23.90	1.25	29.88	17.60	0.60	17.93	**0.36**
Kr	906	34.50	1.25	43.13	18.20	0.60	25.88	**0.52**
Xe	1232	68.10	1.25	85.13	14.20	0.60	51.08	**1.03**
N	234	1.27	1.25	1.59	83.00	0.60	0.95	**0.02**
Ne	321	2.65	1.25	3.31	57.00	0.60	1.99	**0.04**
Ar	642	8.03	1.25	10.04	41.80	0.60	6.02	**0.12**
Cu	1007	18.50	1.25	23.13	30.80	0.60	13.88	**0.28**
Kr	1226	29.00	1.25	36.25	28.00	0.60	21.75	**0.44**
Xe	1955	56.10	1.25	70.13	23.80	0.60	42.08	**0.85**

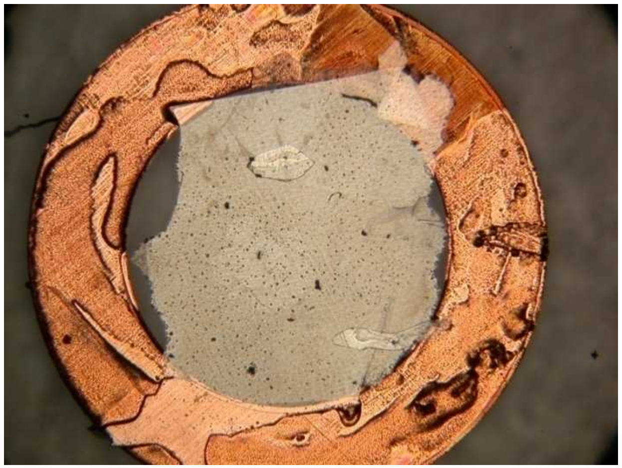
We may have even seen the effect of air luminescence using the alpha-IPEM.

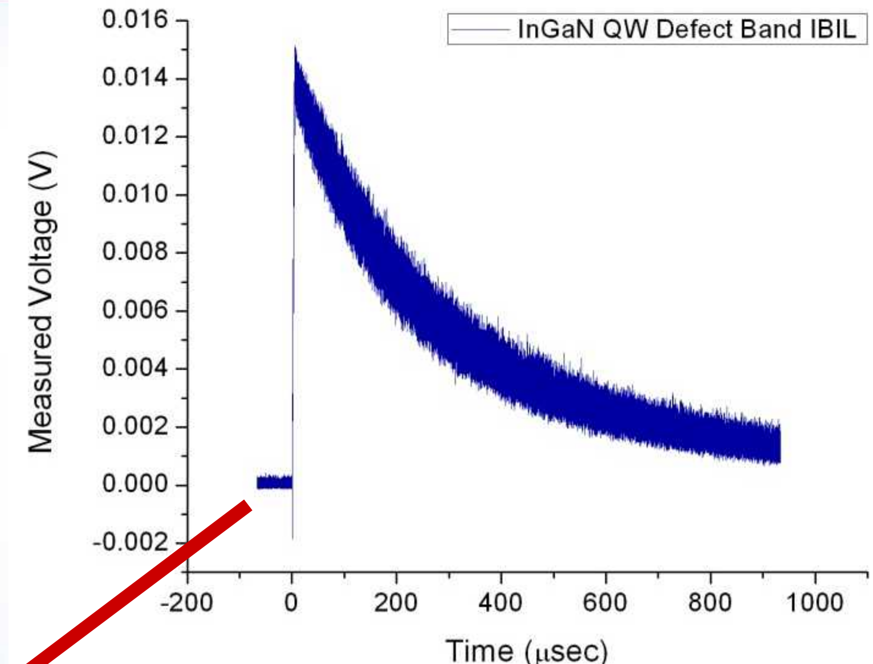


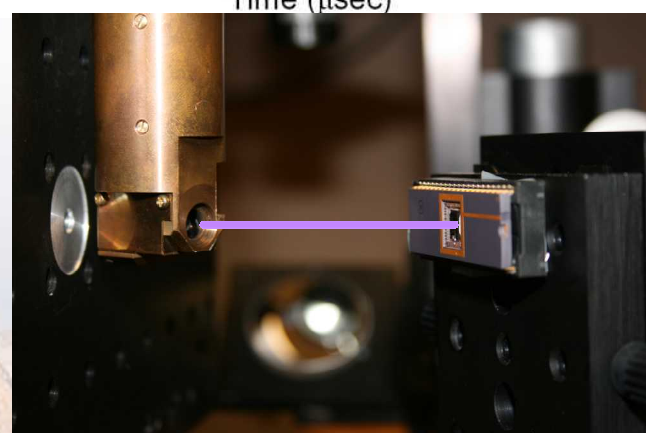


Current Cyclotron IPEM Obstacles

Very Difficult Sample Preparation

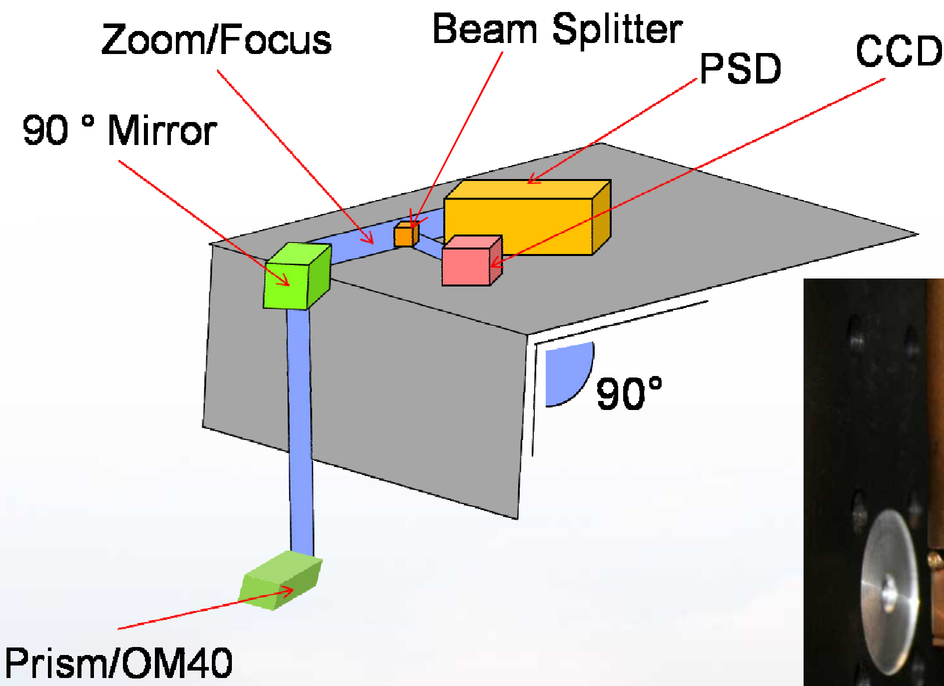




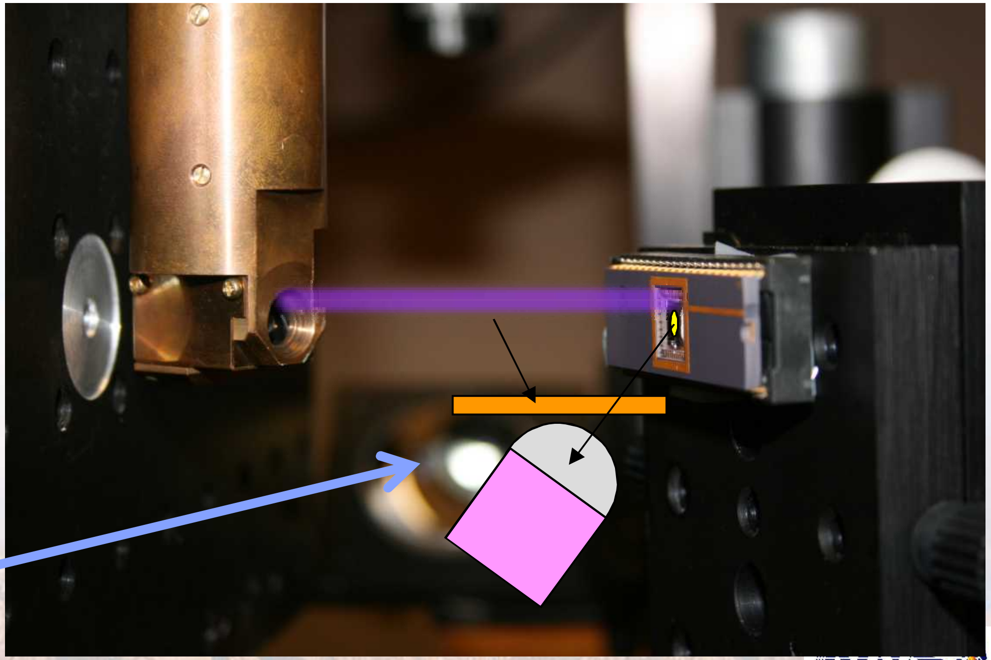


Cyclotron IPEM

Cyclotron IPEM Mark II Schematic

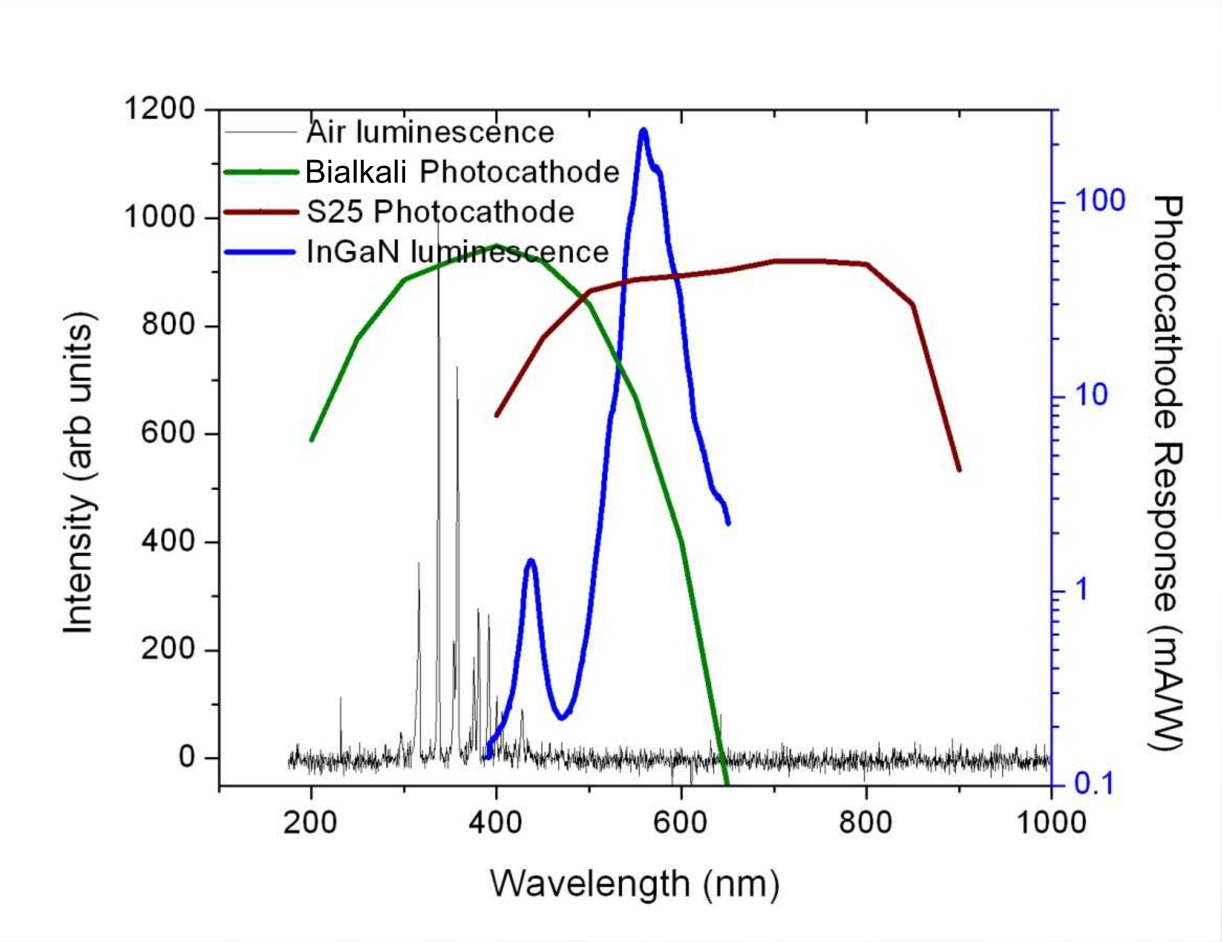


IPEM Microscope and Sample with air luminescence



Include single photon PMT in coincidence with bandpass filter to limit air luminescence accidental coincidences

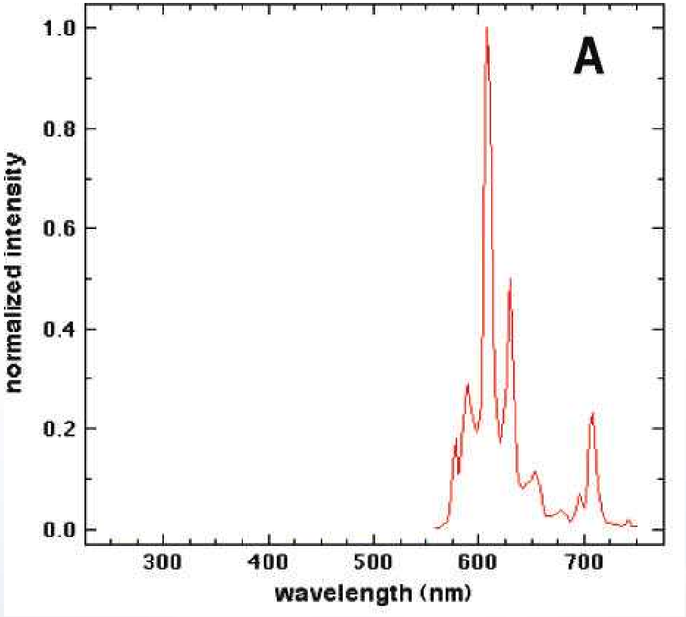
Solutions to Air Luminescence – S25 Photocathode



- While current photocathode (bialkali) is most sensitive in the 250-500 nm region, an S25 has little or no efficiency in region of nitrogen emission

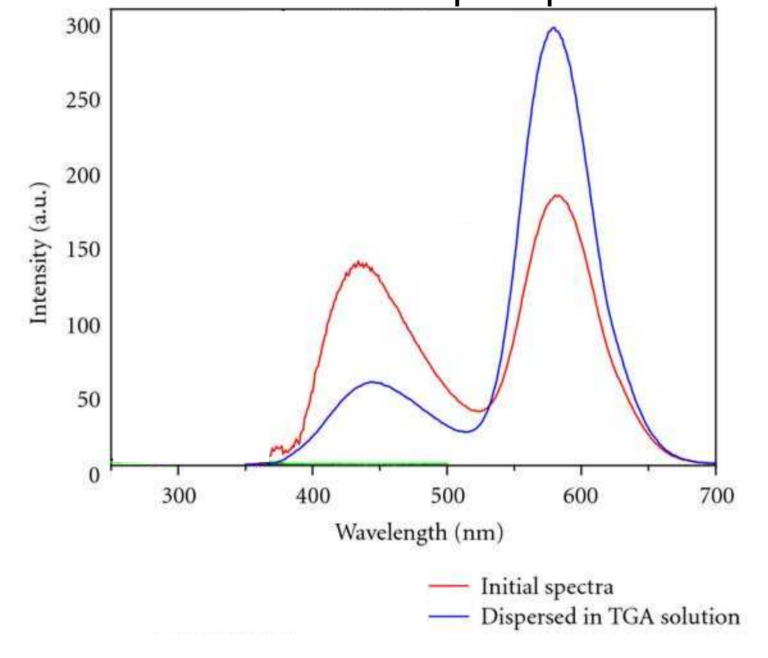
Solutions to Air Luminescence and Fabricability – Red-Emitting Nanophosphors

PL emission (red line) of $KLuTa_2O_7:Eu^{3+}$ nanophosphor



Nyman, M. et al. JACS Communications Online 07/31/2009

PL emission (red line) of ZnS:Mn nanophosphor



Yang, P. and Bredol, M. 2008 Research Letters in Materials Science

- New research in nanophosphors – synthesizing at low temperatures, easy to apply/deposit to chips/devices, high volume densities now available
- Red emission would make it easy to filter out blue/green lines from air

Key Results Obtained To Date

- **Alpha-IPEM**
  - GaN IPEM Layers
    - Photons/ion/MeV plots
    - Lift off
    - Intensity and lifetime
  - 1um resolution slide (used later as regards air flourescence)
- **Tandem-IPEM**
  - Blooming (paolo slide) and Resolution (TEM)
  - IC tests
- **Cyclotron-IPEM**
  - Photo/schematic of system
  - Photo of GaN in washer (=> difficulty applying to sample)
  - Only good data fig
  - Light from airpath
  - Conclusion Fig of all problems
- **Cyclotron-IPEM Mark 2**
  - GaN => nanophosphor sedimentation.
  - Solutions to air flourescence.

In Conclusion (1):

The Radiation Effects Facilities using cyclotrons would benefit by adding Ion Photon Emission Microscopy to enhance their broad beam radiation exposure capabilities.

Radiation Effects Microscopy of Single Event Upsets-Latchups-Burnouts-Transients could then be performed eXternally, in air, thereby pinpointing the root cause of these malfunctions.

This would combine Sandia's recently invented IPEM and the development of the eXternal in-air exposure system, which enable Radiation Effects Microscopy using the extremely high energies (>15 MeV/amu) available on cyclotrons.

The next step would be to find a way to fund this development. Hardware costs would be in the $200K range for a "turn-key" system that users could operate. It will probably cost another $200K in manpower to design, assemble and test the system at Sandia.