The STAR project
(Southern Europe Thomson Backscattering)

Alberto Bacci @ INFN-Milano
On behalf of STAR group (INFN Milano, LNF, UNICAL, CNISM)

Advanced Medical Imaging with Synchrotron and Compton X-ray Sources
21-22 November 2019, Bologna, Italy

The most effective “photon accelerator”

ICS VS FEL

Inverse **C**ompton **S**ource VS **F**ree **E**lectron **L**aser

$[E_{X\gamma-ICS} = 4\gamma^2 E_{laser}]$ VS “$[E_{X\gamma-FEL} = 2\gamma^2 E_{m.static-und.}]$

ICS boost twice than an **FEL** &

much shorter undulators λ_u [μm VS cm]!

1 Å (12.4 keV) a typical goal for

@ XFELs light source

FEL

Accelerator and undulator: $T_{e^-} = 7\ GeV$; $\lambda_u = 2\ cm$

ICS

Accelerator and undulator: $T_{e^-} = 25\ MeV$; $\lambda_u = 1\ \mu m$

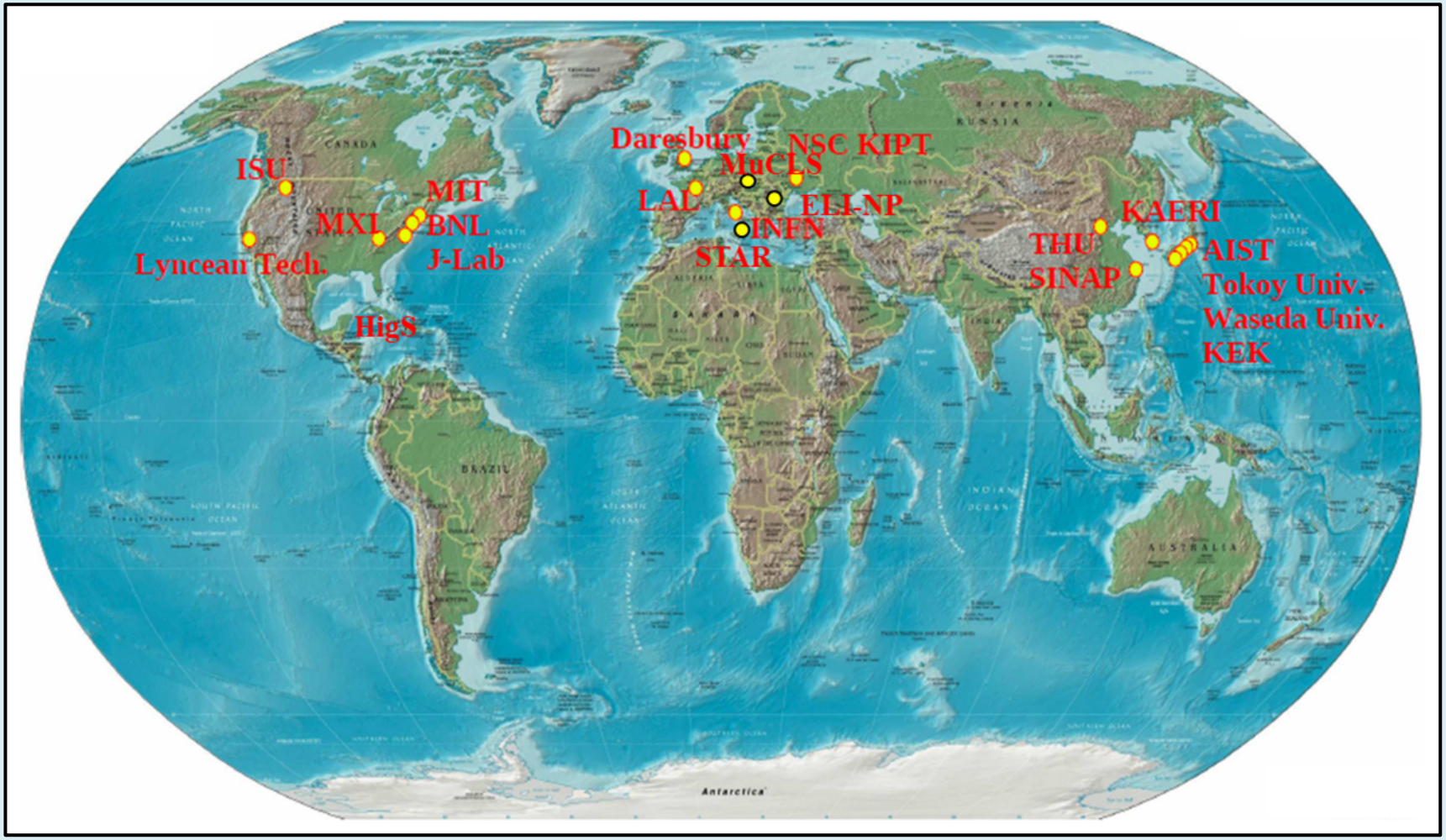
Outline

- Inverse Compton Source (ICS) intro
  1) Worldwide sources panorama
  2) ICS laws of scale
  3) Milano group & ICS:

     SPARC_lab, ELI-np (fresh news), STAR

- The **STAR** project
  1) Location & Funds
  2) Beam-line and main characteristics
  3) Interaction Chamber
  4) From Phase-I → to → Phase-II
  5) Foreseen applications

Worldwide panorama



Existing and planned ICS sources

facilites

*	Type	Energy [KeV]	Flux (@ 10% bandwidth)	Source size (μm)
*PLEIADES (LLNL) [11,12]	Linac	10-100	10^7 (10 Hz)	18
*Vanderbilt [13,14]	Linac	15-50	10^8 (few Hz)	30
*SLAC [15]	Linac	20-85		
*Waseda University [16,17]	Linac	0.25-0.5	2.5 10^4 (5 Hz)	
*AIST, Japan [18]	Linac	10-40	10^6	30
*Tsinguha University [19]	Linac	4.6	1.7 10^4	
*LUCX (KEK) [20]	Linac	33	5 10^4 (12.5 Hz)	80
+ UTNL, Japan [21,22]	Linac	10-40	10^9	
MIT project [23]	Linac	3-30	3 10^{12} (100 MHz)	2
MXI systems [24]	Linac	8-100	10^9 (10Hz)	
SPARC –PLASMONX [25]	Linac	20-380	2 10^8 -2 10^{10}	0.5-13
Quantum Beam (KEK) [26,27]	Linac		10^{13}	3
*TERAS (AIST) [28]	Storage ring	1-40	5 10^4	2
*Lyncean Tech [29,30,31] MuCLS	Storage ring	7-35	~ 10^{12}	30
Kharkov (SNC KIPT) [32]	Storage ring	10-500	2.6 10^{13} (25 MHz)	35
TTX (THU China) [33,34]	Storage ring	20-80	2 10^{12}	35
ThomX France [35]	Storage ring	50	10^{13} (25 MHz)	70

Table 3: Compact Compton X ray sources. Symbols * and + refers respectively to machines in operation and to machines in construction.

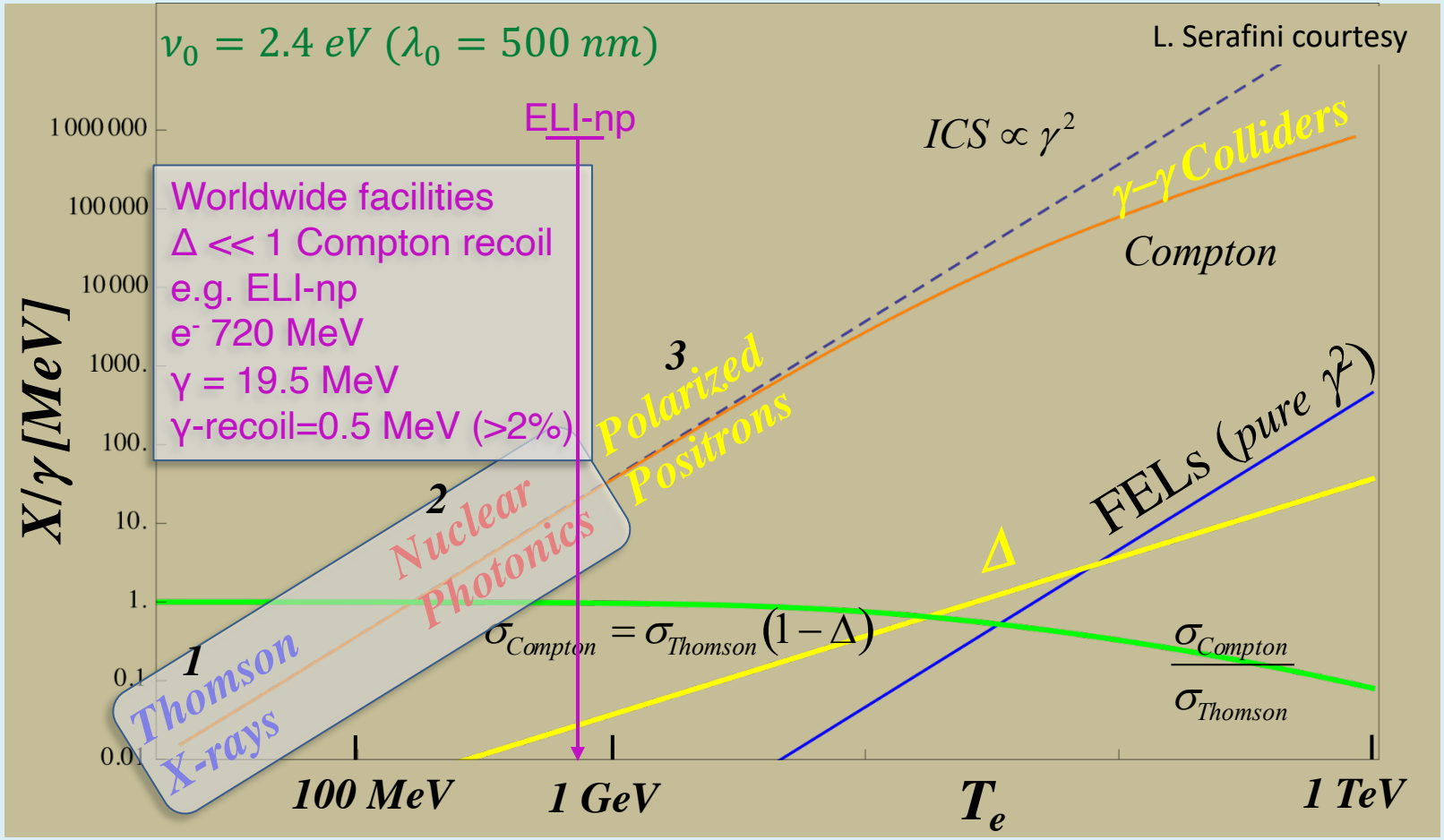
STAR (Calabria)	**Linac**	**20-100**	**10^{10} (100 Hz)**	**18**
ELI-np (Romania)	**Linac**	**0.2-2·10^3**	**10^8 (@ 5‰ bdw)**	**10-30**

* From **THOMX CDR**, A. Variola, A.Loulergue, F.Zomer, LAL RT 09/28, SOLEIL/SOU-RA-2678, 2010

Electron-photon back-scattering

$$\nu_\gamma = \nu_0 \frac{4\gamma^2}{1+\gamma^2\theta^2 + a_0^2/2}(1-\Delta)_{recoil}$$

$$\Delta = \frac{4\gamma h\nu_0}{mc^2}$$



BD Milano group & ICS

- (SPARC_LAB @ INFN Frascati Lab) first Italian ICS,
  NIM A 829 (2016) 237-342.

- STAR @ 20 to 140 keV.
  Beams we hope in next monthsSPARC_lab.

- **E**xtreme **L**ight **I**nfrastructure-**n**uclear **p**hysics, **ELI-np**
  - 3.2 kHz rep rate
  - c-band linac booster at 100Hz (for a 32 bunches train), T_{max}=720 MeV
  - Laser pulse recirculated 32 times

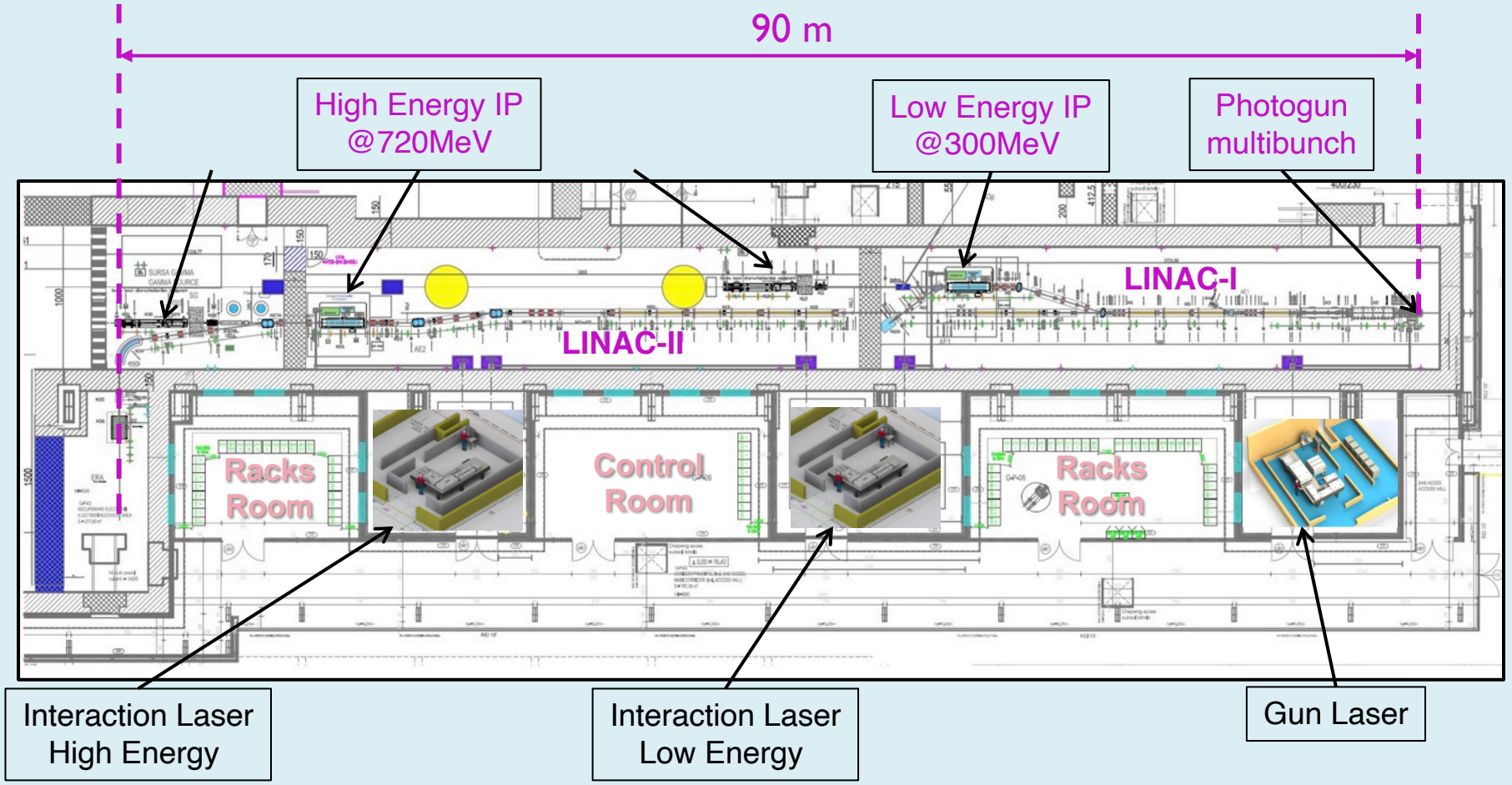
  - Max γ-ray energy: 19.5 MeV (0.5% bdw)
  - Flux: ph/sec (within FWHM)=$8 \cdot 10^8$

A big machine: ELI-NP news

World's largest laser lab rocked by slew of disputes

Delays and disagreements plague final stages of the world-leading, €875-million Extreme Light Infrastructure being built across Eastern Europe.

Nature ***569***, *607-608 (May 2019) doi: 10.1038/d41586-019-01607-7*



STAR Project

Actors in the project :

Partners

- **UNICAL** (**UNI**versità della **CAL**abria), machine site
- **CNISM** (**C**onsorzio **N**azionale **I**nteruniversitario per le **S**cienze fisiche della **M**ateria, i.e. **Italian Consortium on Physical Sciences of Matter**)

Collaborators

- **Elettra Sincrotrone Trieste**
- **INFN** (**I**stituto **N**azionale di **F**isica **N**ucleare)

UNIVERSITÀ DELLA CALABRIA

cnism

Elettra Sincrotrone Trieste

INFN

Location

University of Calabria (UNICAL):

International Architect competition in 1974 (won by Gregotti Bureau), built in 1977

- 35.000 Students
- Well known Physics department

Location & Funds

Calabria was and is Eligibility for European Funding:

PON (**P**rogramma **O**perativo **N**azionale)

National Competition Europen Funding for **school** and **research**

Linac based research infrastructure, into an University campus.
It is really an unique reality in Italy

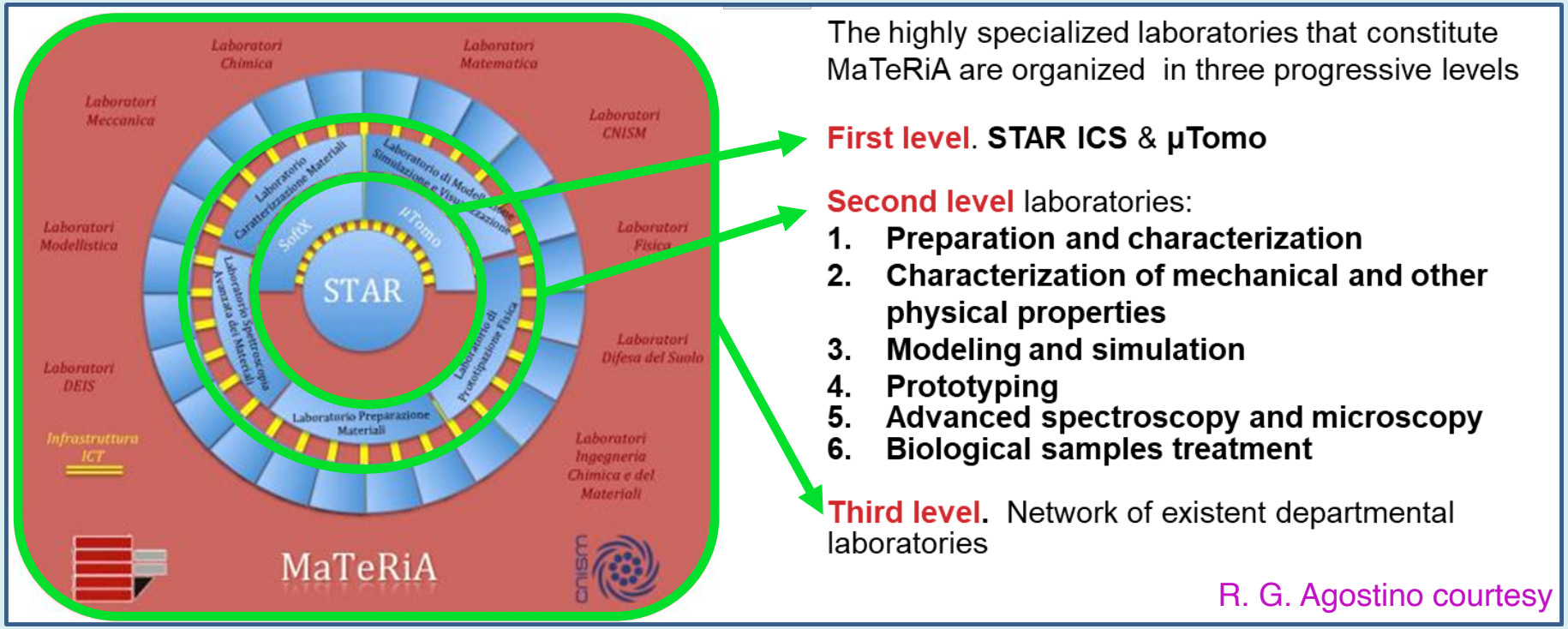
STAR in a nut shell

An 100Hz ICS monochromatic & tunable & ps-long & polarized X-Ray beam SOURCE.

- Phase 1 (Max. e^- energy 85 MeV): 20 to 140 keV photons
- Phase 2 (Max. e^- energy 190 MeV): up to 700 keV

- **Experiments:** material science (electronics, mechanics, energy-related materials, …); non-invasive diagnostics for **cultural heritage**; bio-medical radiological imaging; …

Infrastructure **MaTeRia** (**Ma**teriali, **Te**cnologie, **Ri**cerca)**:** three level



The highly specialized laboratories that constitute MaTeRiA are organized in three progressive levels

First level. **STAR ICS** & **µTomo**

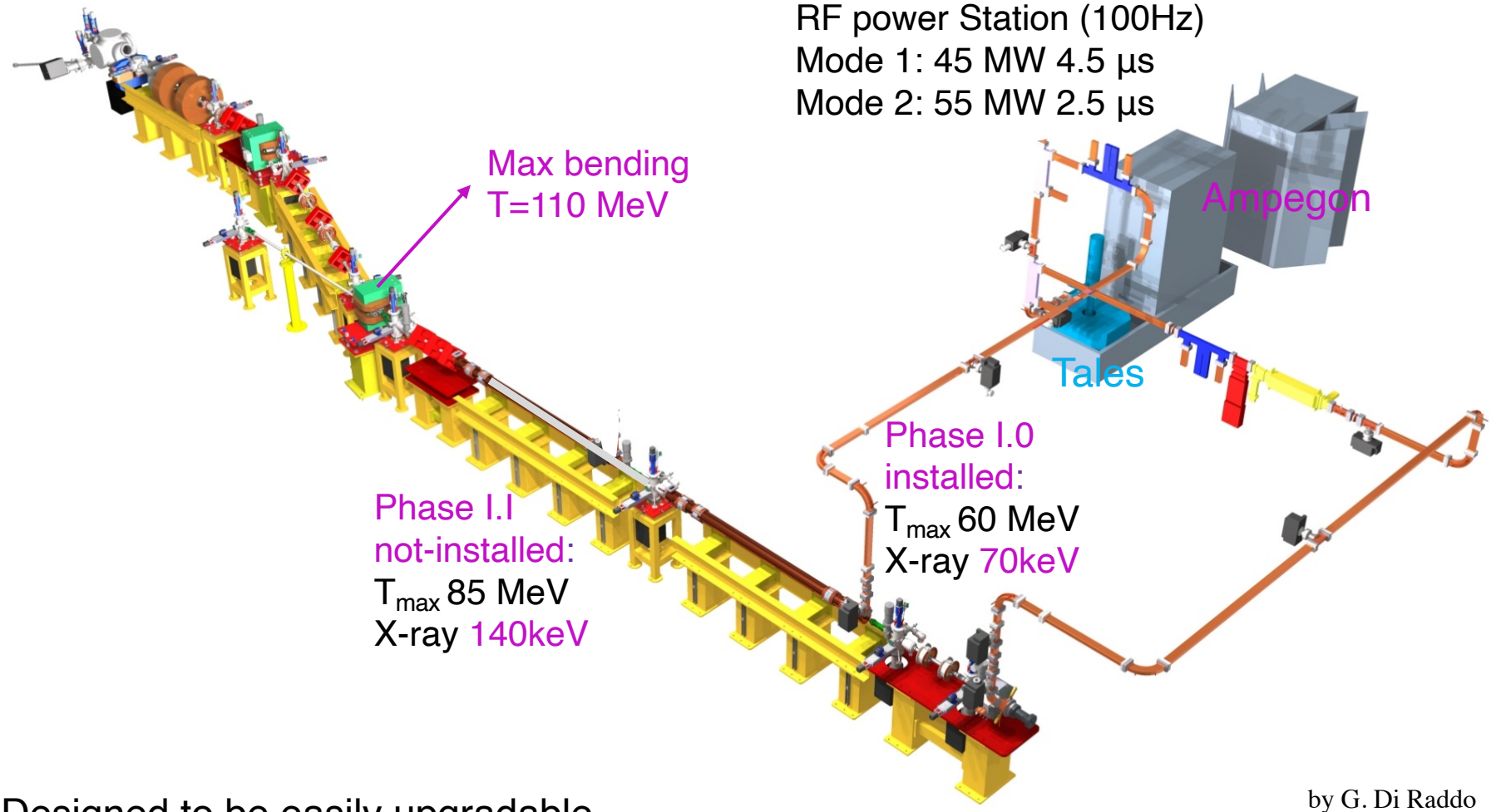
Second level laboratories:

1. **Preparation and characterization**
2. **Characterization of mechanical and other physical properties**
3. **Modeling and simulation**
4. **Prototyping**
5. **Advanced spectroscopy and microscopy**
6. **Biological samples treatment**

Third level. Network of existent departmental laboratories

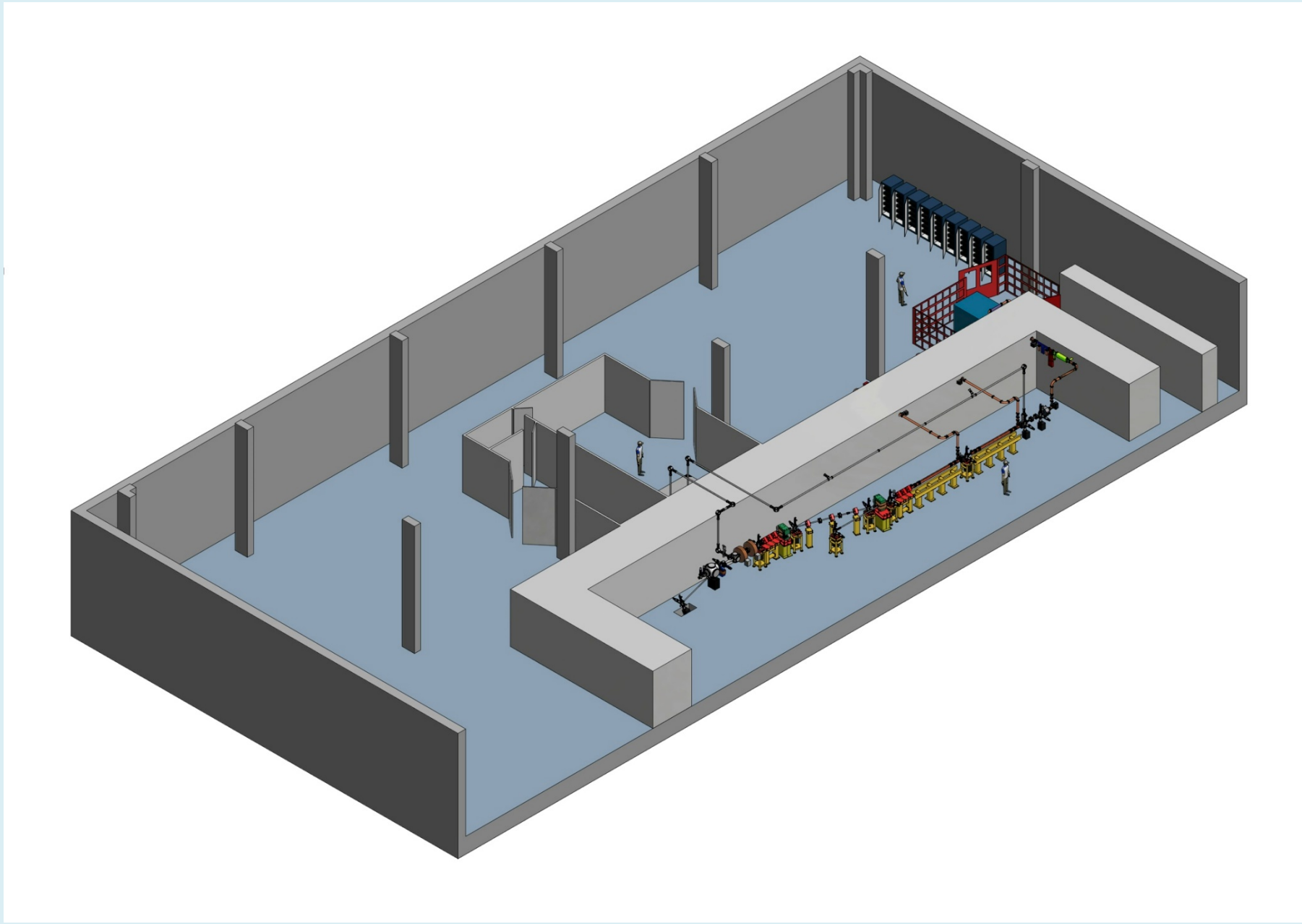
R. G. Agostino courtesy

STAR machine layout

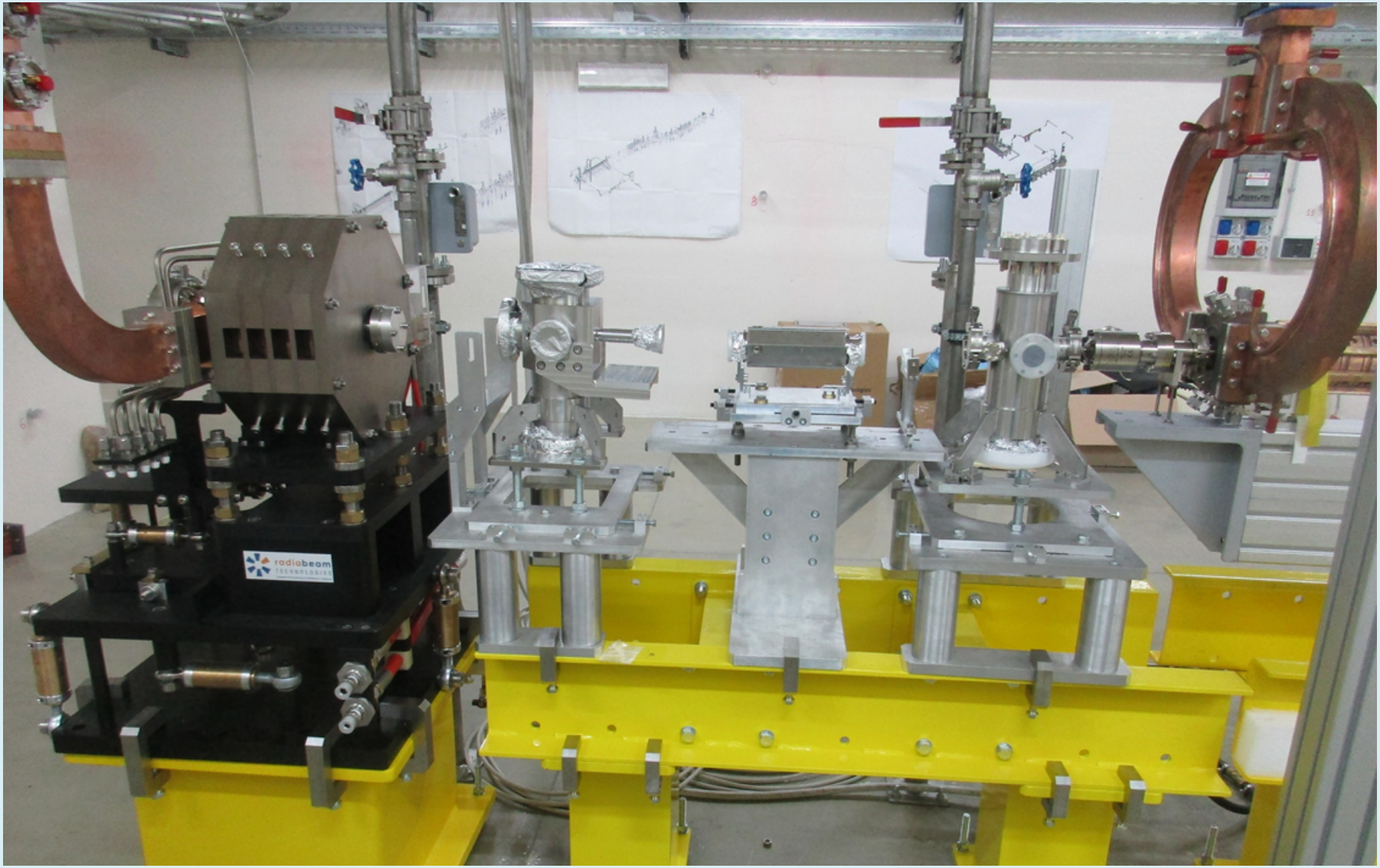


Designed to be easily upgradable

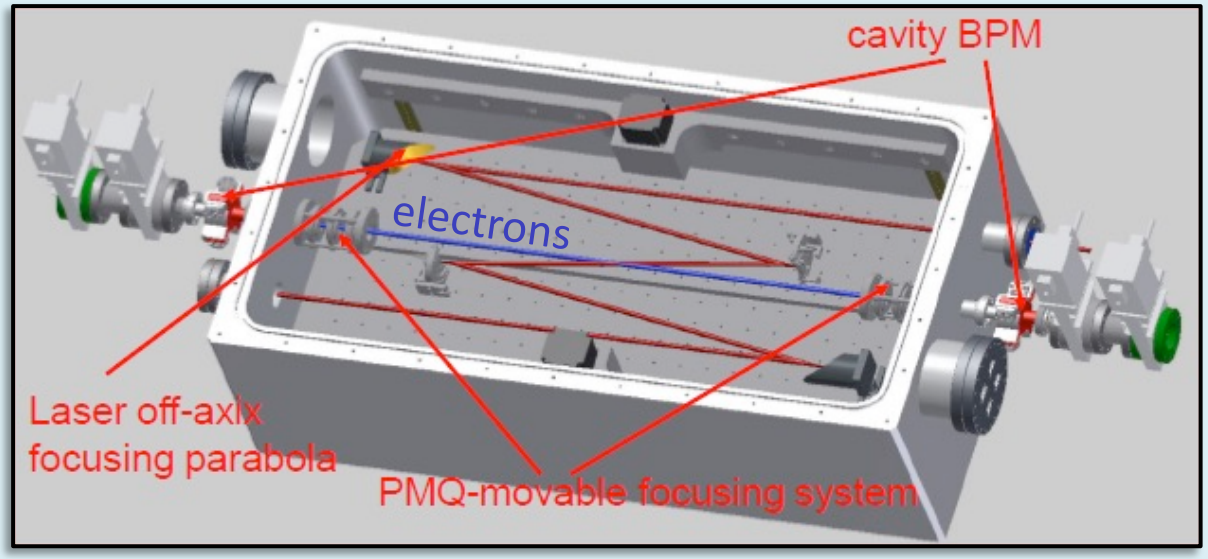
by G. Di Raddo



Stato Bunker STAR a Gennaio 2016

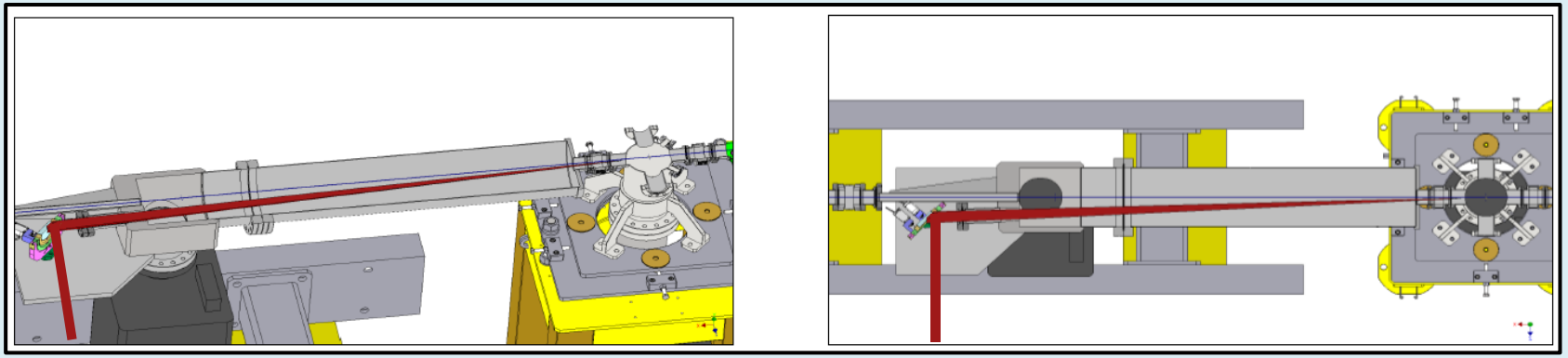

radiabeam
TECHNOLOGIES

Old & new interaction chamber design

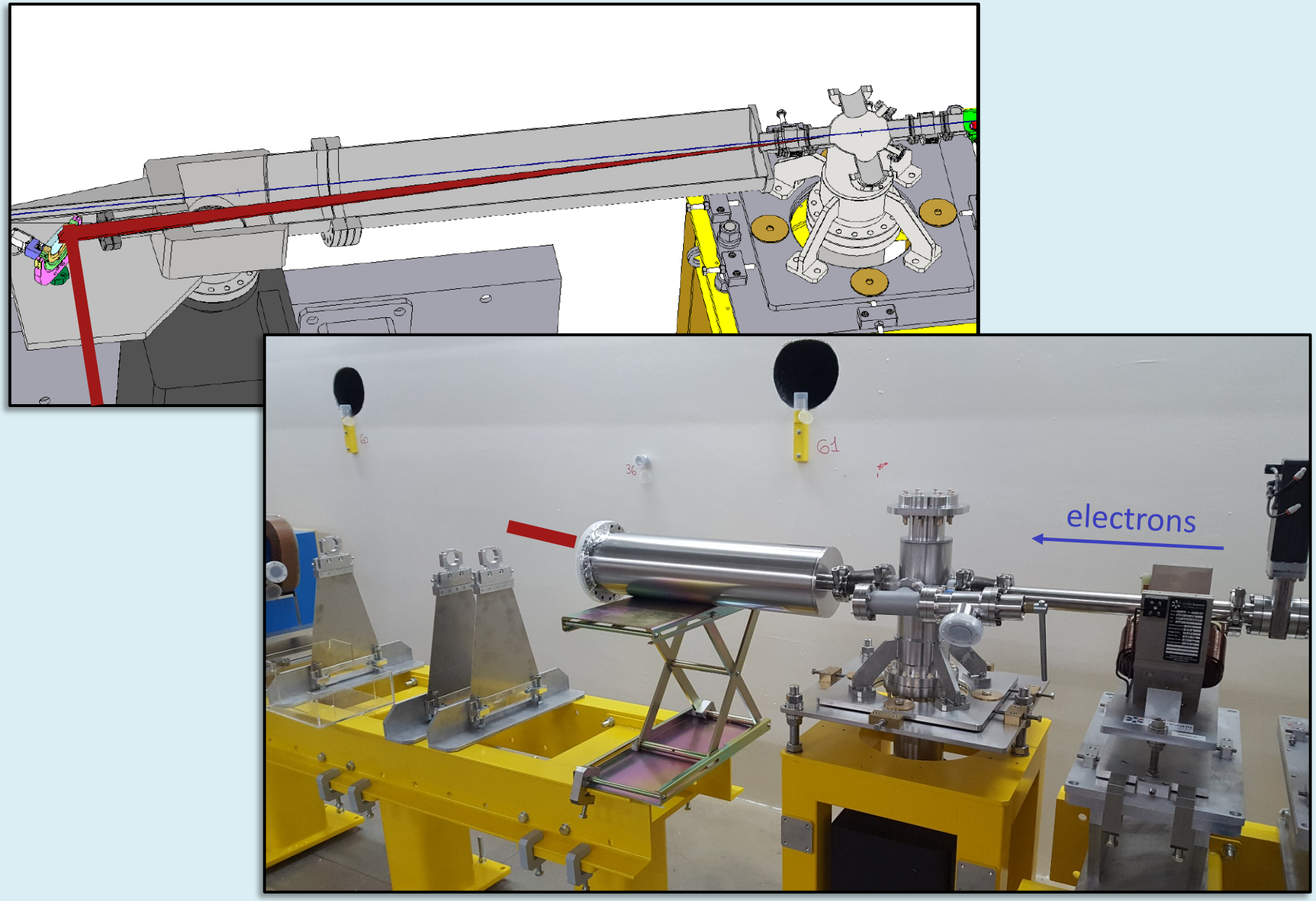


Very expensive: ~ 200k
maybe for phase-II

New scheme: ~ 20k



A diagnostic chamber, with an ad hoc laser entrance

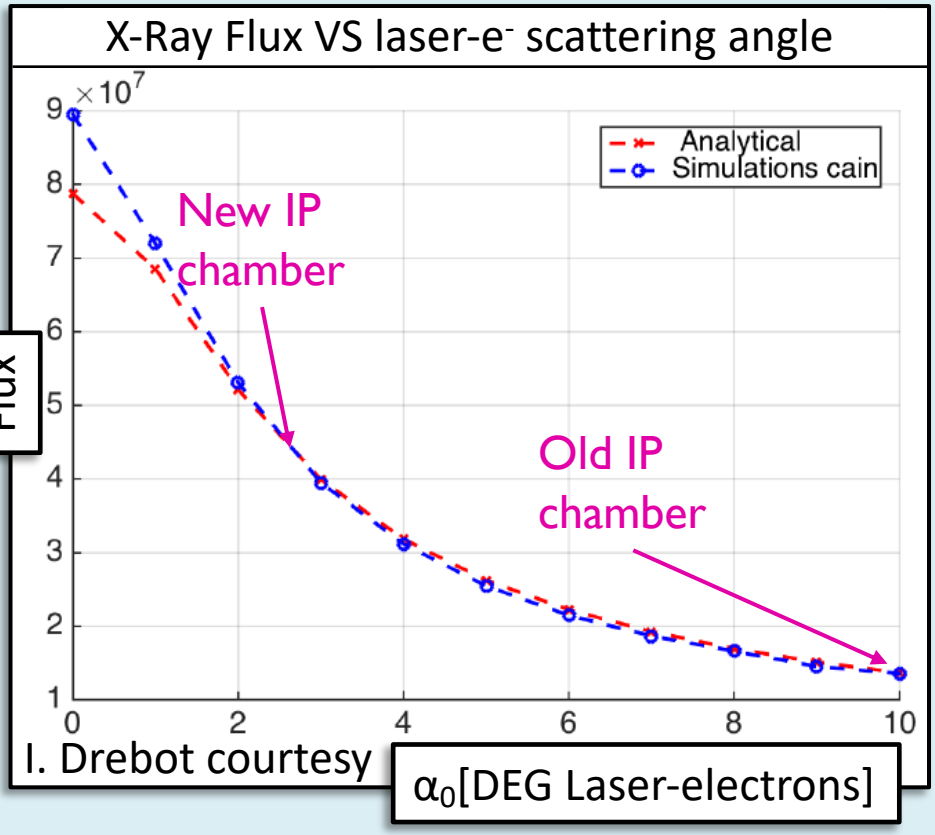

electrons

5 m long DogLeg: 20deg for 60 MeV beam

Wavelength (nm)	258+/-1	1030+/-1	1030+/-1
Jitter (ps rms 10Hz-10kHz)	<1	<1	<1
Bandwidth (nm)	<1	<1,5	<1
Strehl ratio	NA	>0,8	>0,8
M^2	1,3	NA	NA

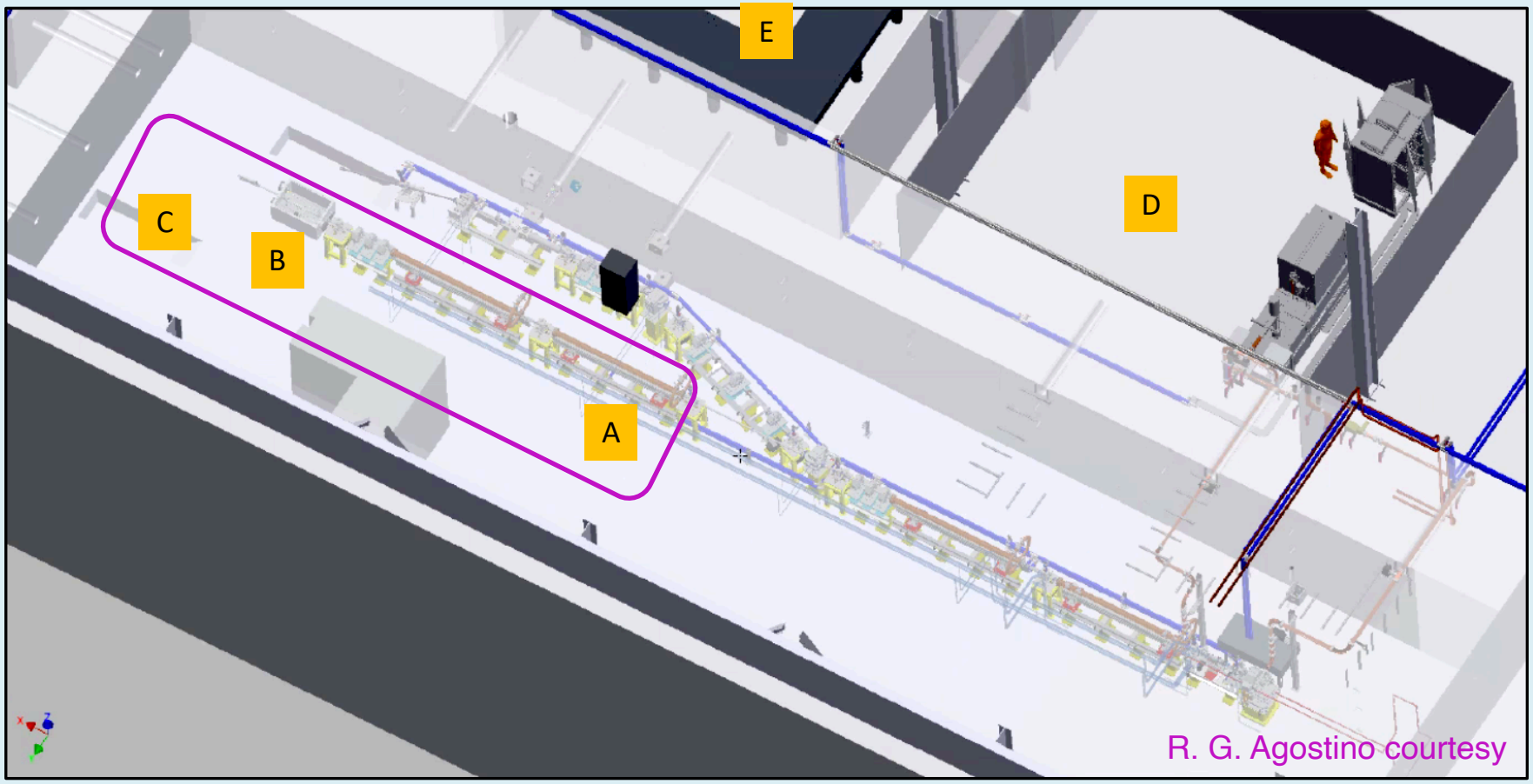
** It has been measured few days ago a value of 150 mJ

Source performances – some data



Electron beam Parameters	
Electron Energy [MeV]	59.81
Bunch charge [nC]	0.5
Bunch length rms [mm]	0.93
Normalize Emit. x,y [um]	1.4, 2.1
Energy Spread %	0.2
Spot size rms; x,y@ IP	9.5, 13.2
Interaction Laser Parameters	
Pulse energy [mJ]	130
Pulse Lenght rms [ps]	1.9
Spot size w0, rms [um]	28
Wavelegth [nm]	1030

STAR phase 2



STAR UPGRADE PHASE-II (60 → 190 MeV)

A. NEW High Energy branch (190 MeV)
B. Interaction chamber
C. Beam dump
D. NEW RF power station
E. Upgrade laser system (130 mmJ →1 J)

STAR phase-1

STAR operating modes	High-flux Medical imag.	Small-BW Better detectio/dose performnace	Short-pulse Pump & probe experiments
Photon energy (keV)	20-140	20-140	40-140
Photons/s (@100 Hz)	2-4*10^9	2-4*10^8	2-4*10^6
Bandwidth (rms)	10%	1%	1%
Rms Pulse lenght (ps)	1-5	1-5	<0.2

ICS linac driven are:
- easily tunable
- easily upgradable

STAR phase-2

	STAR-HE	STAR-LE
Photon energy (keV)	**70-700**	**20-180**
Photons/s (@100 Hz)	**10^{11}**	**10^{11}**
Bandwidth (rms)	1-10%	1-10%
Rms Pulse lenght (ps)	0.2-5	0.2-5

- *The Star project, Proceedings of IPAC2014, Dresden, Germany*
- *Status of the Star project, Proceedings of IPAC2016, Busan, Korea*
- *Photoinjector Emittance Measurement at STAR", Proc. of IPAC2017, Copenhagen, Denmark*

Foreseen applications

Already exist main USERS:
UNICAL Departments &
existing national and international collaboration

- Electronic Engineering Dept. **&** ST Microelectronics samples
- Humanistic science Dept. **&** Danish National Foundation
- Earth Science (Mineralogy)
- Biology Dept. **&** UniBa Biology Dept. **&** Mayo Clinic, Rochester Univ., USA
- Metallurgy @ Rina Consulting SpA (Hydrogen embrittlement in steel)
- Civil Engineering Dept. (Composite materials for civil engineering)

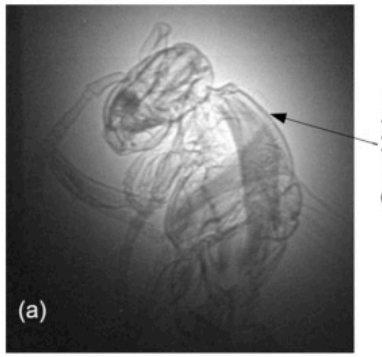
Example applications

APPLIED PHYSICS LETTERS **97**, 134104 (2010)

Quantitative evaluation of single-shot inline phase contrast imaging using an inverse compton x-ray source

P. Oliva,[1,a)] M. Carpinelli,[1] B. Golosio,[1] P. Delogu,[2,3] M. Endrizzi,[3,4] J. Park,[5] I. Pogorelsky,[5] V. Yakimenko,[5] O. Williams,[6] and J. Rosenzweig[6]

At brookhaven national laboratory



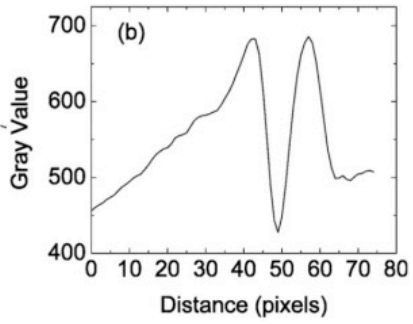
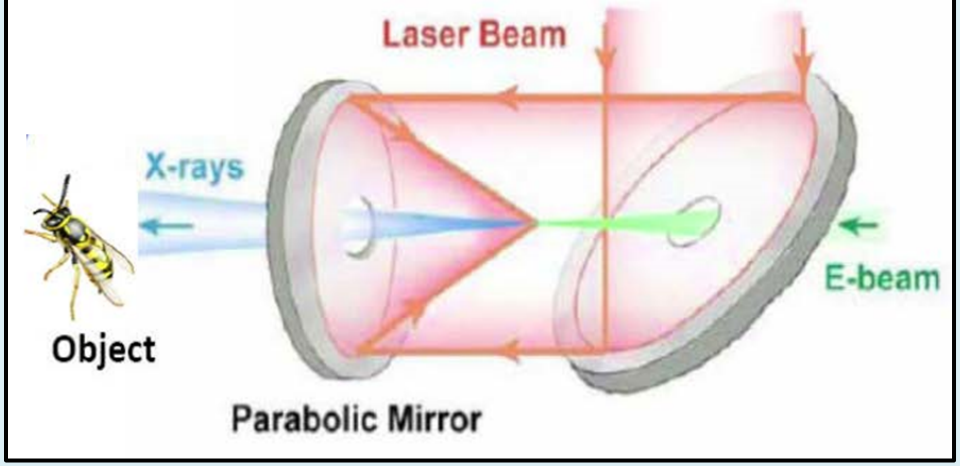
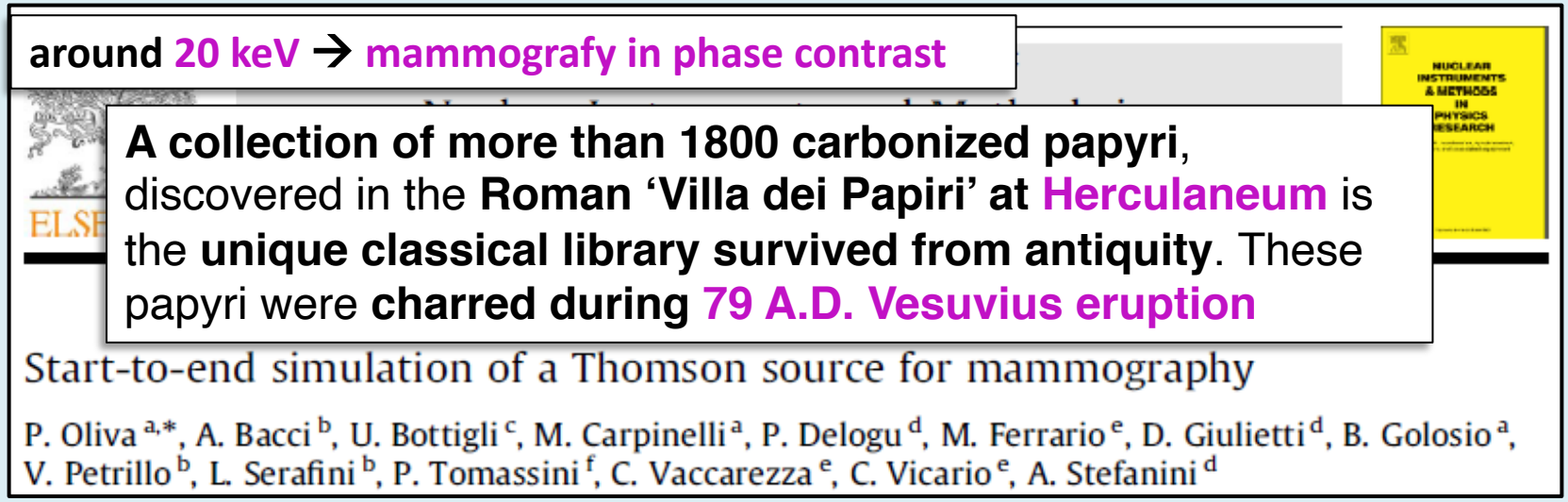


FIG. 2. Single-shot image of a wasp (a). Intensity profile in the box on the border of the back of the insect (b). The inline PhC is clearly visible.



Example applications

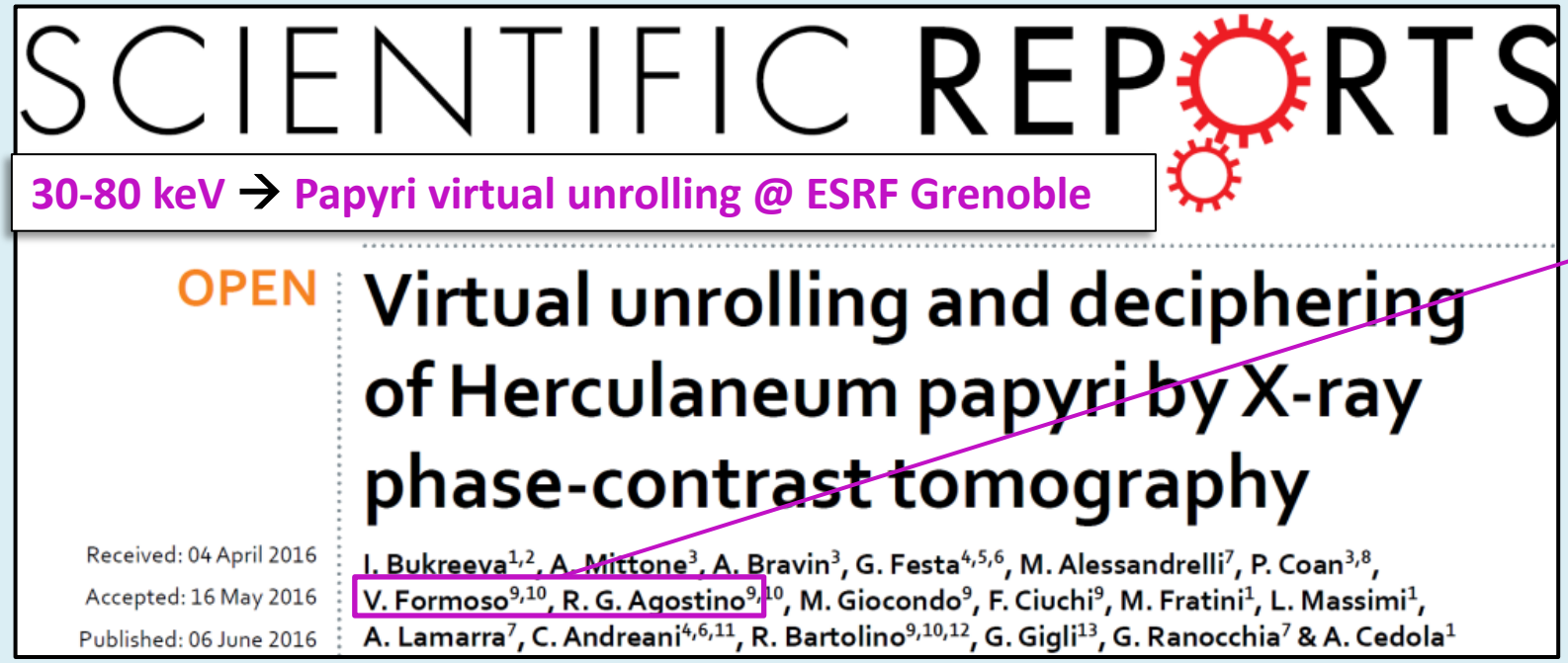
around 20 keV → mammografy in phase contrast



A collection of more than 1800 carbonized papyri, discovered in the **Roman 'Villa dei Papiri' at Herculaneum** is the **unique classical library survived from antiquity**. These papyri were **charred during 79 A.D. Vesuvius eruption**

Start-to-end simulation of a Thomson source for mammography

P. Oliva [a,*], A. Bacci [b], U. Bottigli [c], M. Carpinelli [a], P. Delogu [d], M. Ferrario [e], D. Giulietti [d], B. Golosio [a], V. Petrillo [b], L. Serafini [b], P. Tomassini [f], C. Vaccarezza [e], C. Vicario [e], A. Stefanini [d]



SCIENTIFIC REPORTS

30-80 keV → Papyri virtual unrolling @ ESRF Grenoble

OPEN

Virtual unrolling and deciphering of Herculaneum papyri by X-ray phase-contrast tomography

Received: 04 April 2016
Accepted: 16 May 2016
Published: 06 June 2016

I. Bukreeva[1,2], A. Mittone[3], A. Bravin[3], G. Festa[4,5,6], M. Alessandrelli[7], P. Coan[3,8], V. Formoso[9,10], R. G. Agostino[9,10], M. Giocondo[9], F. Ciuchi[9], M. Fratini[1], L. Massimi[1], A. Lamarra[7], C. Andreani[4,6,11], R. Bartolino[9,10,12], G. Gigli[13], G. Ranocchia[7] & A. Cedola[1]

@ UNICAL STAR team

nature COMMUNICATIONS

ARTICLE

Received 17 May 2014 | Accepted 19 Nov 2014 | Published 20 Jan 2015

DOI: 10.1038/ncomms6895

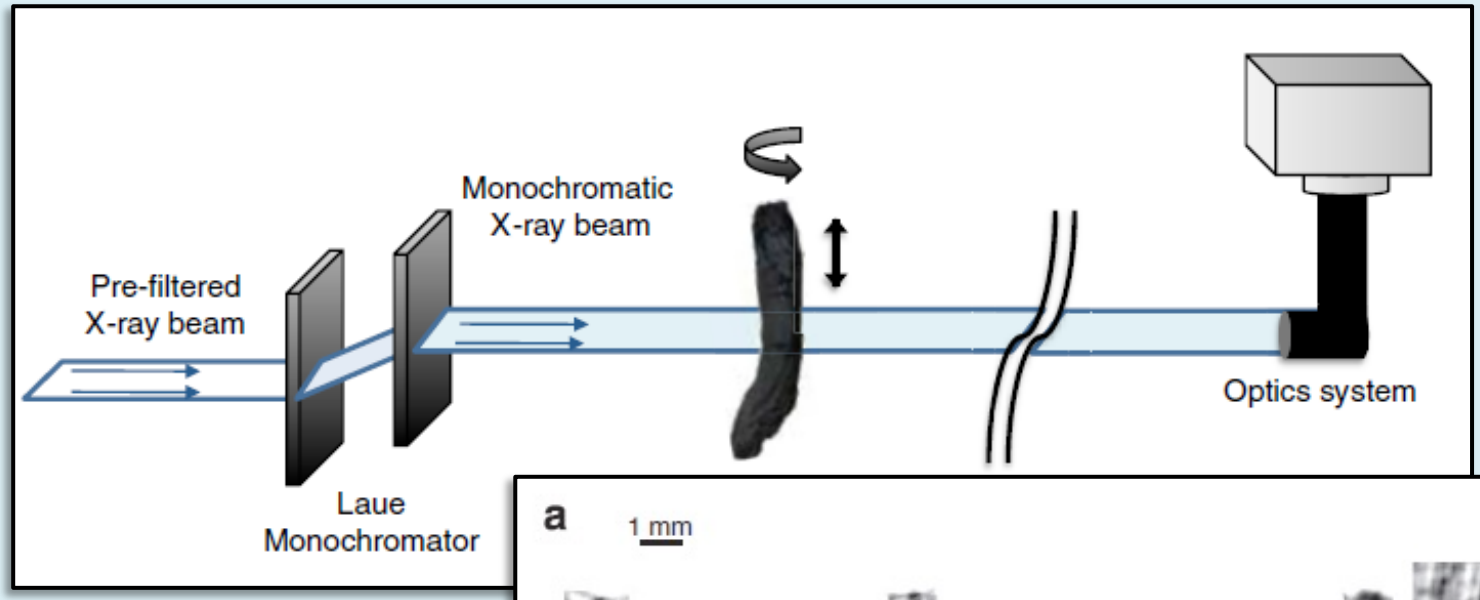
Revealing letters in rolled Herculaneum papyri by X

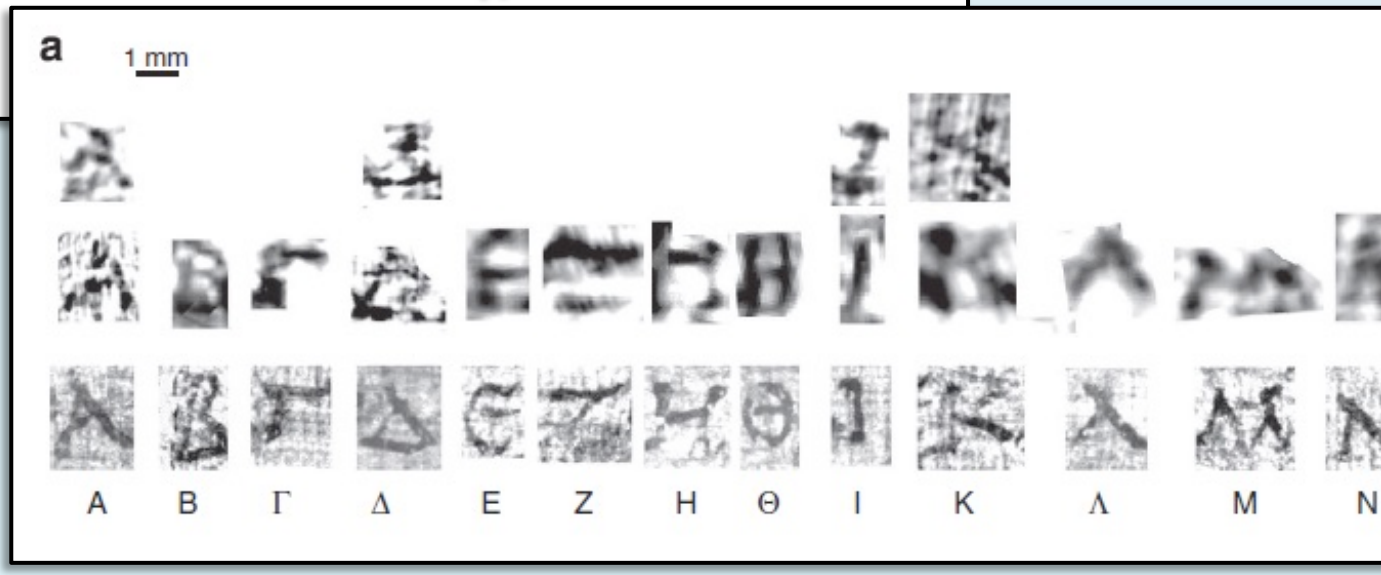
Vito Mocella[1,*], Emmanue

Method

Phase-contrast imaging (**ESRF**, Grenoble, France).

The **optimum energy** of the X-ray beam used was **70 keV** … higher than 75–80 KeV lead to a lower readability of characters





Calabria: rich in archaeological sites and findings

List of Calabrian's museumes:

1)
2)
3)
4)
5)
6)
7)
8)
9)
10)
11)

List of archaeological sites or area

1) Area archeologica di Casignana
2) Area archeologica di Monasterace
3) Sito archeologico di Castiglione di Paludi
4) Sito archeologico di Francavilla Marittima
5) Sito archeologico di Punta Alice
6) Area archeologica di Vibo Valentia
7) Area archeologica di Capo Colonna
8) Area archeologica di Locri Epizefiri
9) Area archeologica di Sibari
10) Area archeologica di Scolacium

PEACE SYMBOLS IN CALABRIA BEFORE GREEK COLONIZATION (A preliminary study @ STAR µTomo)

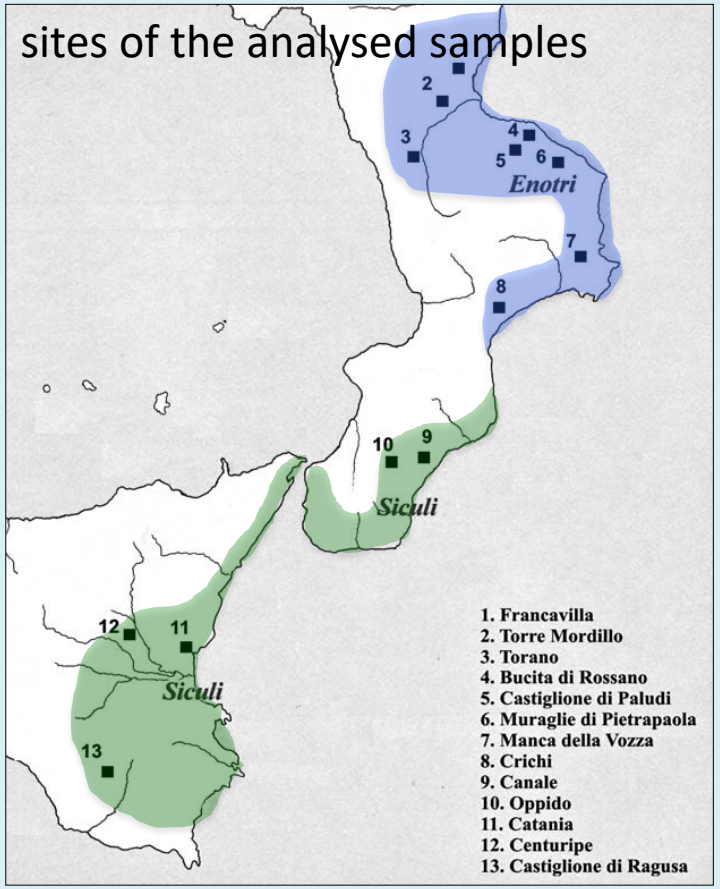
type-A

1. - Pendaglio a coppia antropomorfa da Francavilla Marittima tipo A (lato 1 e 2).

type-B

2. - Pendaglio a coppia antropomorfa da Francavilla Marittima tipo B (lato 1 e 2).

- Bronze anthropomorphic couples as pendants.
- Burial goods in calabrian area (VIII sec B.C.)
- Two sets: type-A (30 findings);type-B (2 findings)

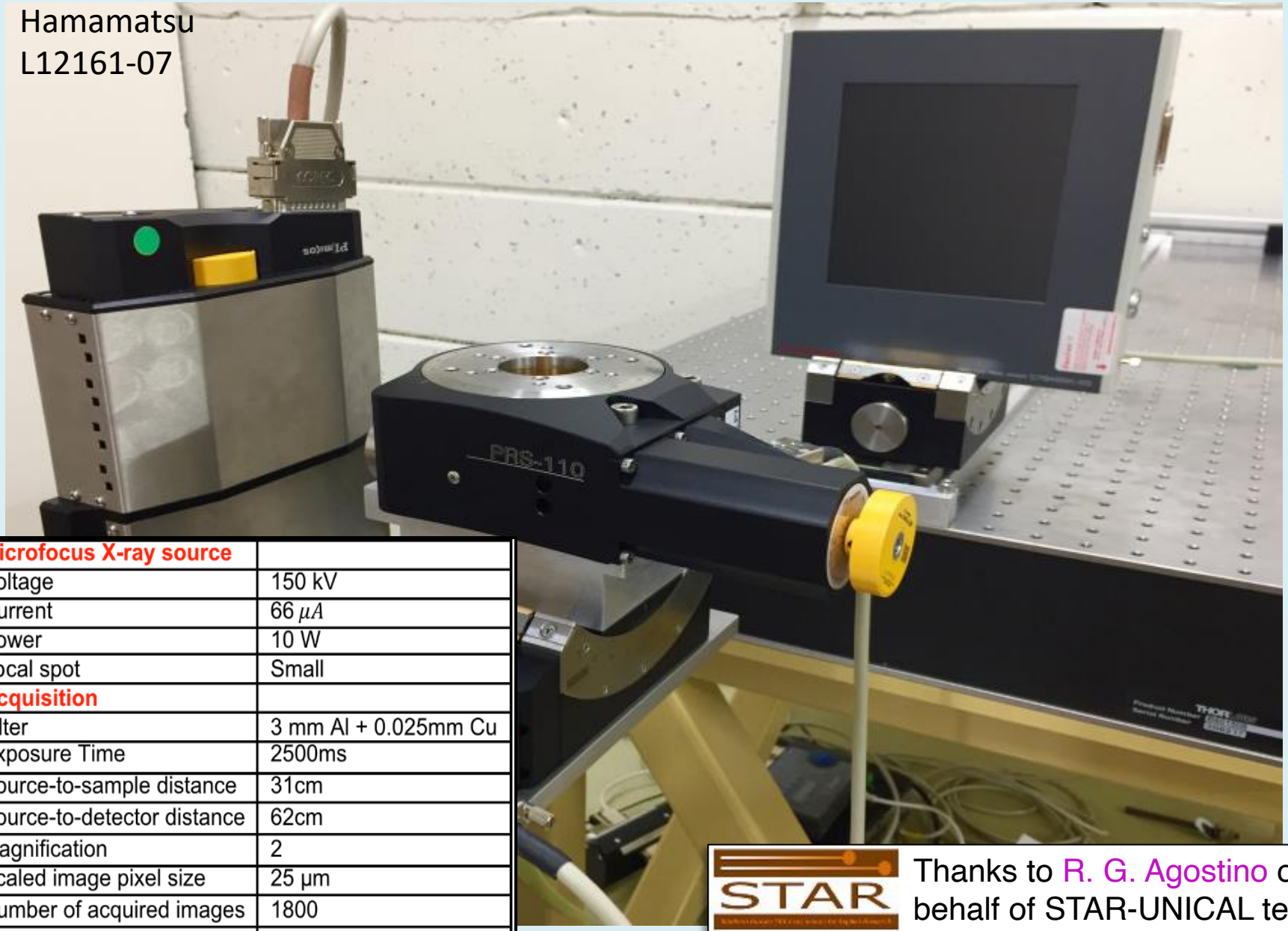


6. - Carta di distribuzione dei pendagli a coppia antropomorfa.

Thanks to R. G. Agostino on behalf of STAR-UNICAL team

P. Brocato e A. Taliano Grasso - Simboli per riti di pace nella Calabria pregreca. Alcune osservazioni sui pendenti a coppia antropomorfa - in MITI DI GUERRA RITI DI PACE. La guerra e la pace: un confronto interdisciplinare - 2011 · Edipuglia

Layout: X-ray microtomography@μTomo experimental station



Microfocus X-ray source	
Voltage	150 kV
Current	66 μA
Power	10 W
Focal spot	Small
Acquisition	
Filter	3 mm Al + 0.025mm Cu
Exposure Time	2500ms
Source-to-sample distance	31cm
Source-to-detector distance	62cm
Magnification	2
Scaled image pixel size	25 µm
Number of acquired images	1800
Step	0.2

Thanks to R. G. Agostino on behalf of STAR-UNICAL team

Results: X-ray micrography

Sample

Projections

Tomography

STAR
Southern Europe TBS x-ray source for Applied Research

Thanks to R. G. Agostino on behalf of STAR-UNICAL team

Peace symbol preliminary results

Campione ROS 1 - Bucita - RS 001

- **Chronological order** and evolution
- **Production techniques**: alloy melting and removal/addition.
- **Production site** : Compare finds from different sites and different cultural.
  Validate M. Kleibrink hypothesis that states Francavilla as production site.

STAR
Southern Europe TBS x-ray source for Applied Research
Thanks to R. G. Agostino on behalf of STAR-UNICAL team

Conclusions

Two considerations:

- Synchrotrons need huge infrastructures to overcome 100keV X-Ray strong limitation in FLUX other the critical energy
- ICS (scaling with γ^2)

Further: 20-150keV S-band technology **10mx10M€**
20-1.0 MeV x-band technology 10m x …? (same scale)

ICS: in last few years simulations **&** experimental results have shown great benefits in more fields.
It is credible that ICS will be much more fruitful and widespread in the next decade

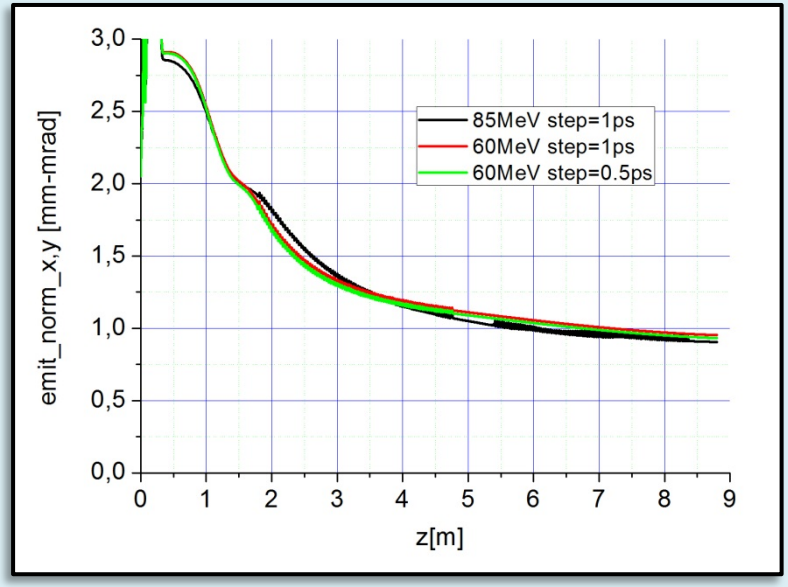
Thanks for your attention

- Two new γ/n monitors arriving before the 2019 end
- Final authorization to switch on and reach maximum energy before the 2019 end
- All gates necessary for safety authorization are installed
- Last measurement of the high power laser shows 150 mJ than 130 mJ panned

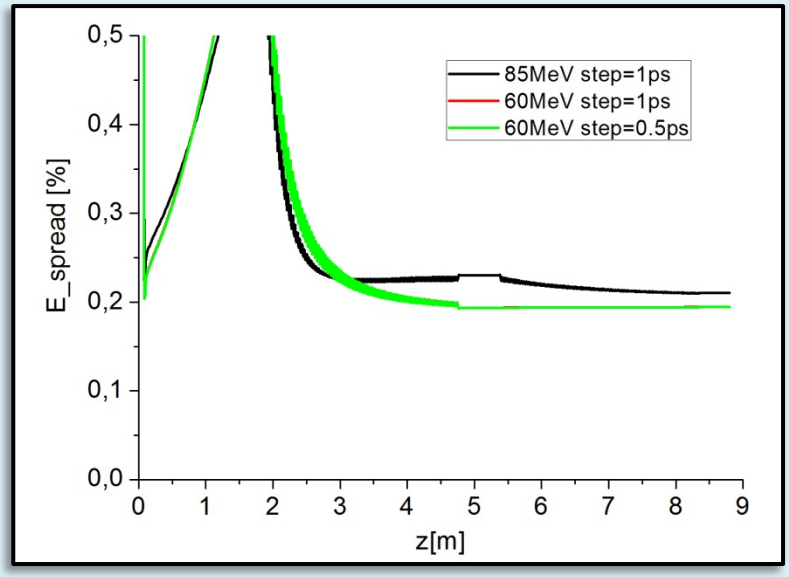
DB for two reference cases: 85MeV and 60MeV

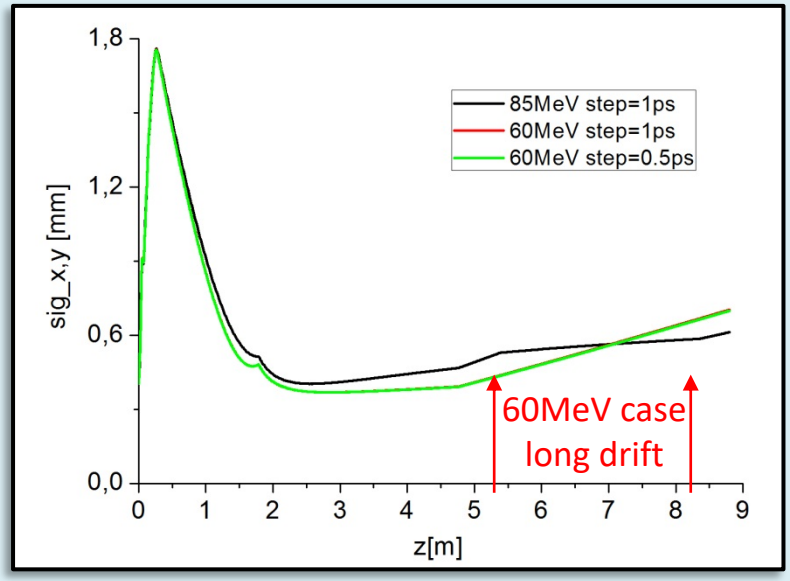
60 MeV – ONE SLAC-type cavity
Q=0.5 nC;
Laser pulse shaping: σ_t=3.4ps (Gaussian)
σ_x=340 μm

85 MeV – TWO SLAC-type cavity
Q=0.5 nC;
Laser pulse shaping: σ_t=3.7ps
σ_x=320 μm

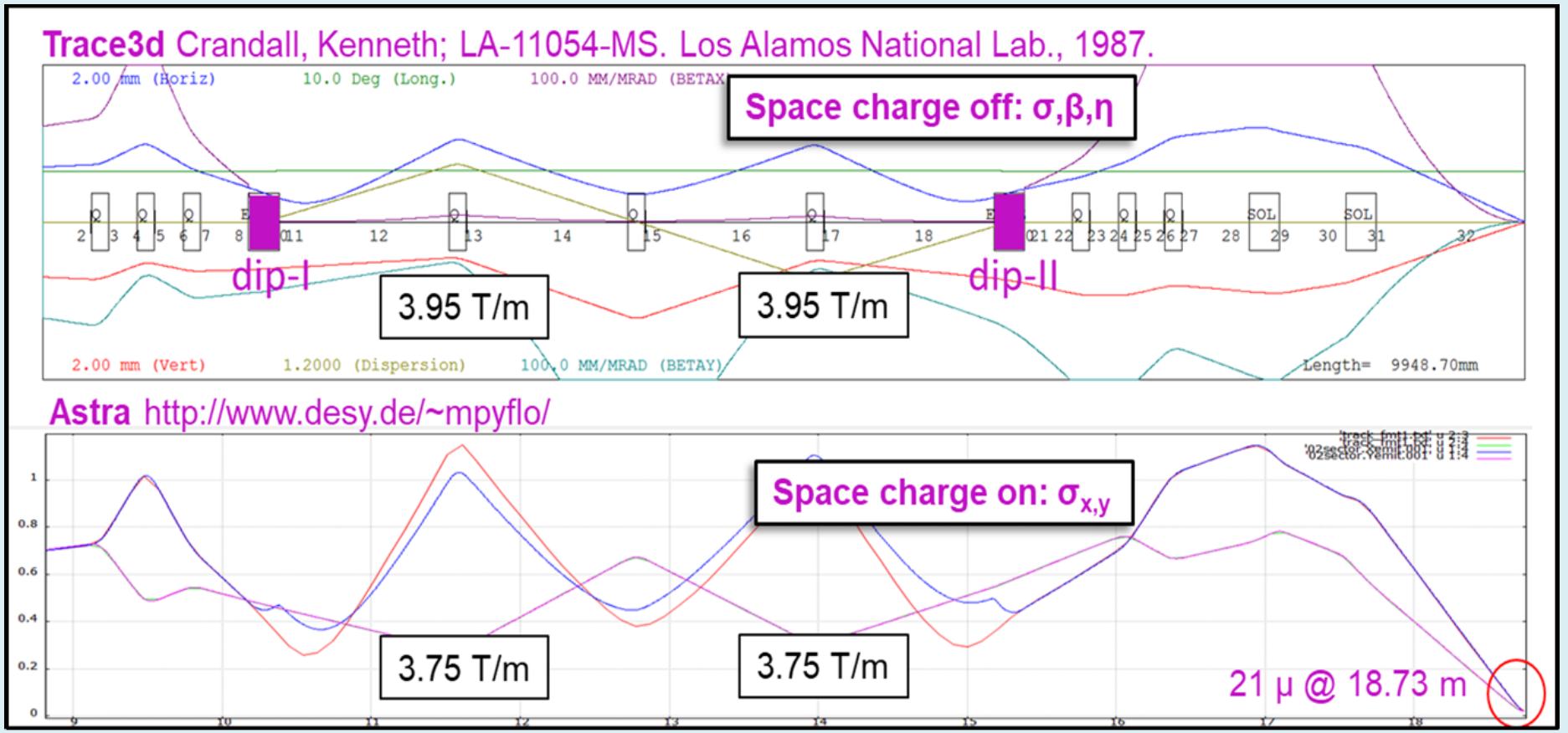


5000mp Astra simulations





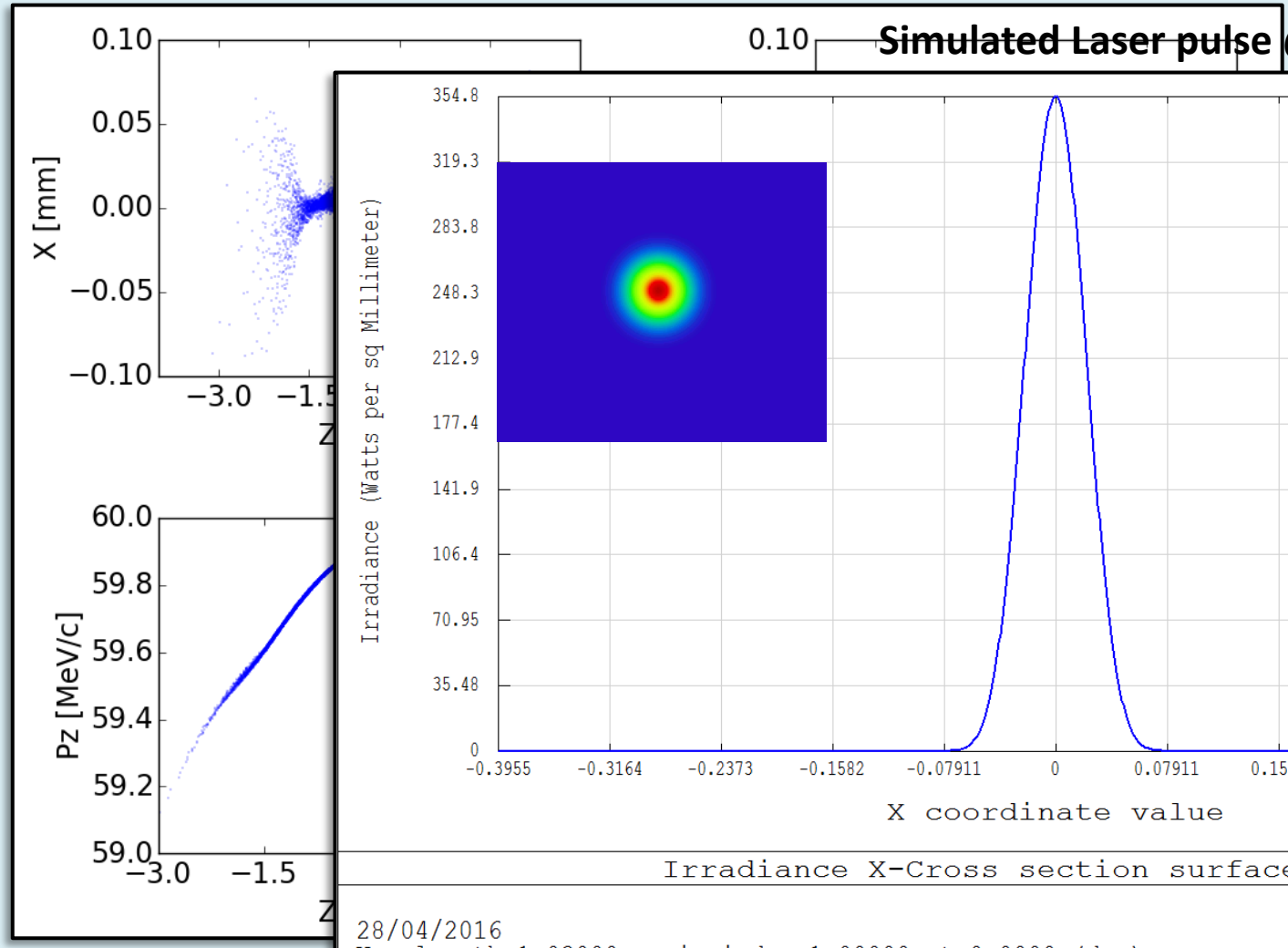
5 m long DogLeg: 20deg for 60 MeV beam



Interatcion Point

Source performances 1/2

Simulated Electron Bunch @ Interaction Point

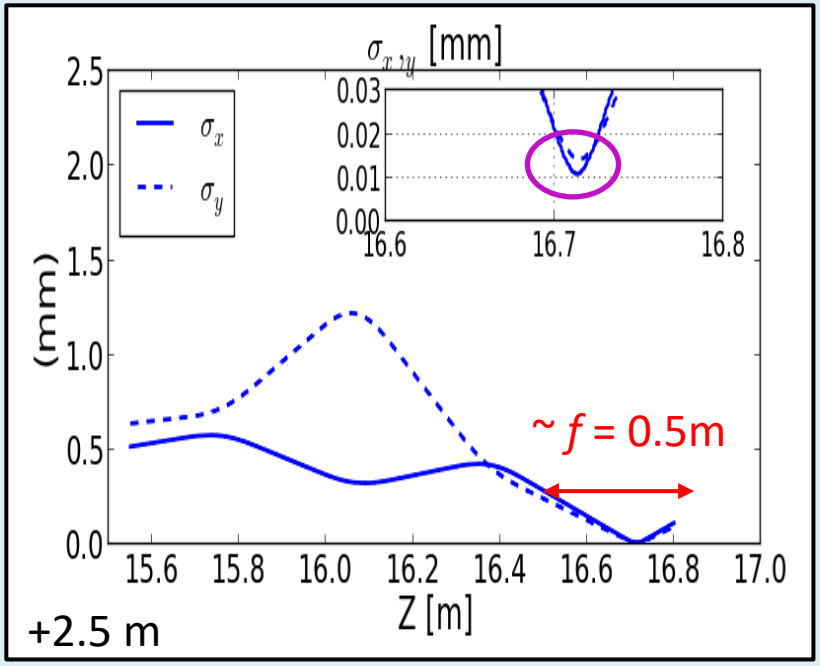


Simulated Laser pulse @ Interaction Point

The Focusing channel

We compared more solutions: Permanent Quad, Solenoids & classical Quad.

Final Fusing Channel



PEACE SYMBOLS: preliminary results

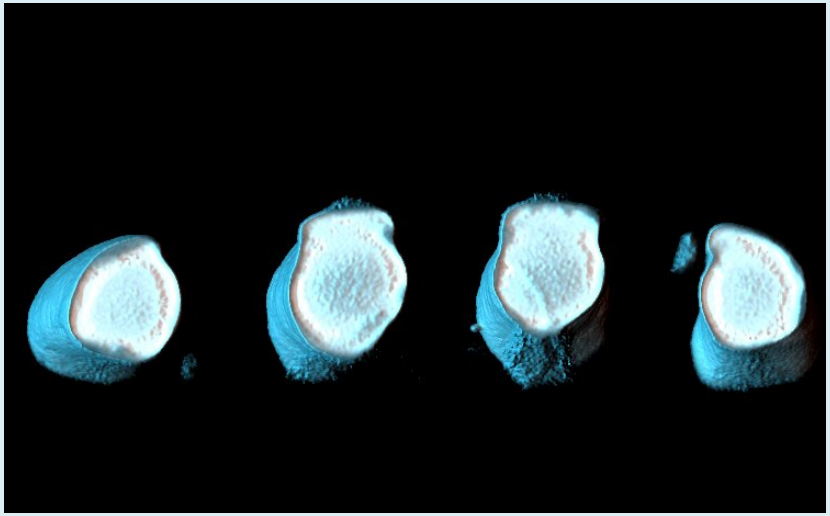
Type A

- Forms by pouring molten metal into a mould
- No evidence of addition
- No anatomic details
- No holes

A raw pendant – This type A finding was not refined.

Type B

- Functional necklet hole
- Detailed anatomic features
- Presence of protrusions/additions (knees, arms, genitals, ...)
- Advanced technique



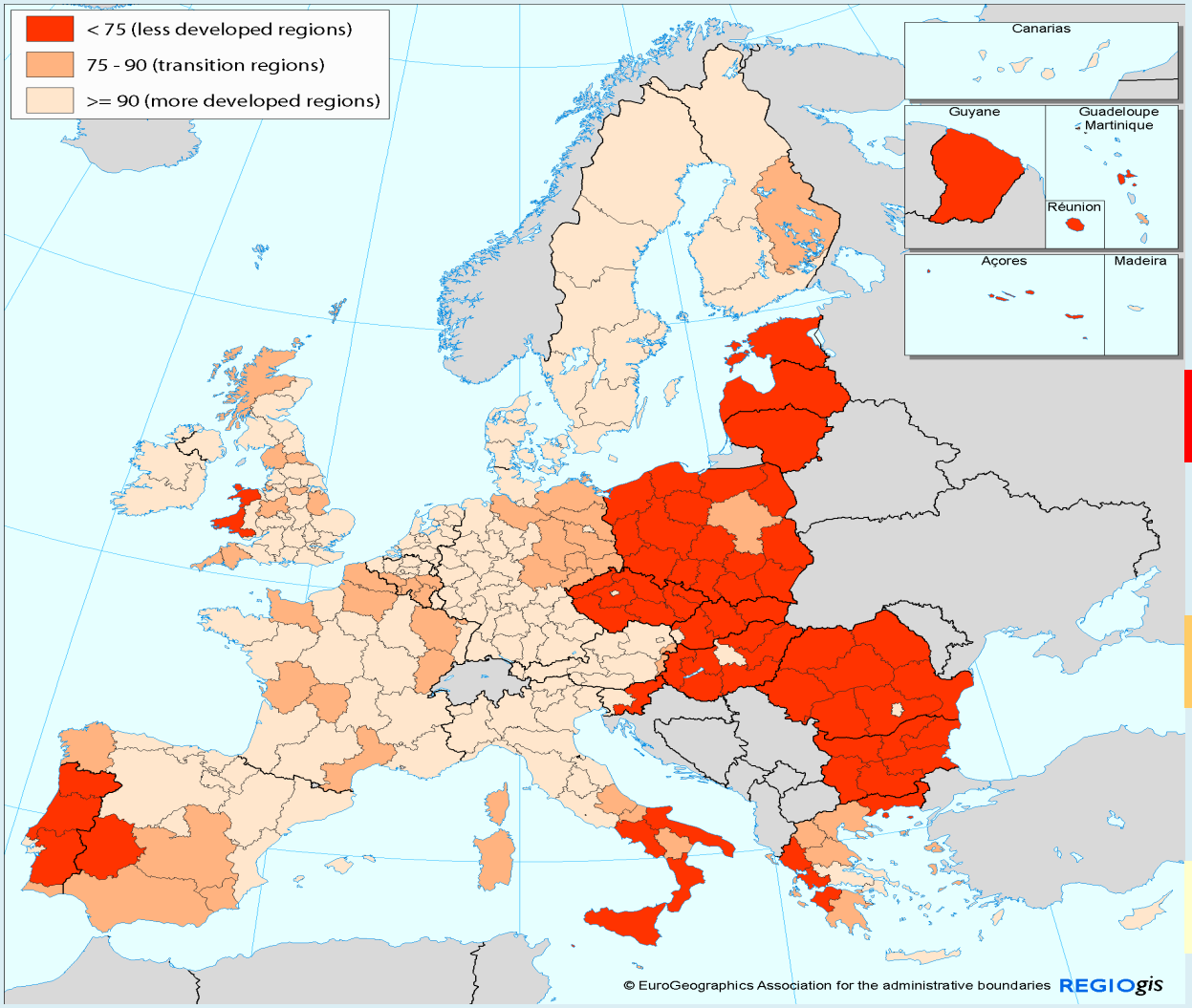
Presence of additions on the knees

STAR
Southern Europe TBS x-ray source for Applied Research

Thanks to R. G. Agostino on behalf of STAR-UNICAL team

Eligibility simulation 2014-2020

GDP/head (PPS), index EU27=100



Less developed regions

Transition regions

Most developed regions

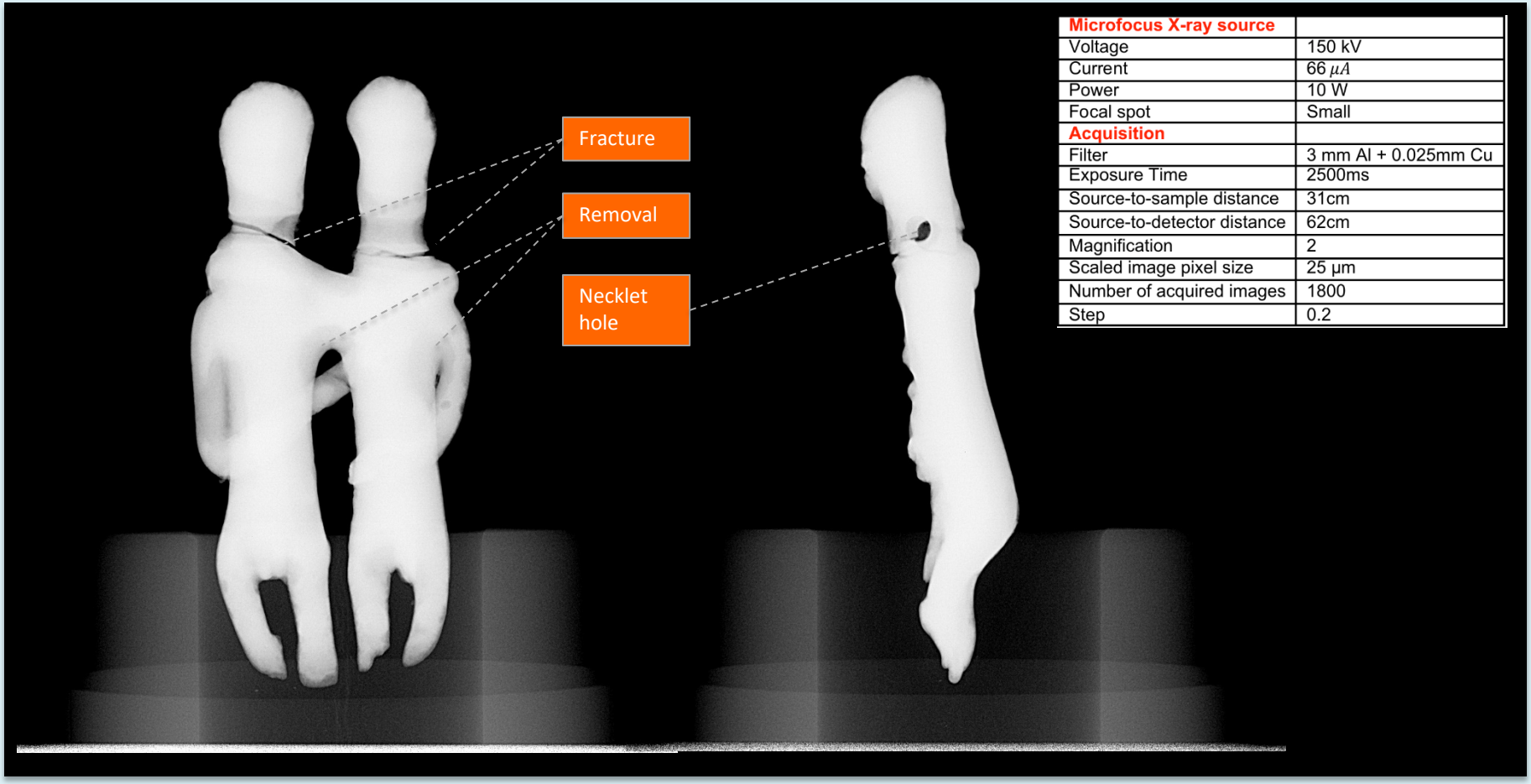
Eligibility for European Funding:

PON (**P**rogramma **O**perativo **N**azionale)

National Competition Europen Funding for **school** and **research**

Anthropomorphic couples: Type B

Results: X-ray Micrography



Microfocus X-ray source	
Voltage	150 kV
Current	66 μA
Power	10 W
Focal spot	Small
Acquisition	
Filter	3 mm Al + 0.025mm Cu
Exposure Time	2500ms
Source-to-sample distance	31cm
Source-to-detector distance	62cm
Magnification	2
Scaled image pixel size	25 µm
Number of acquired images	1800
Step	0.2

STAR
Southern Europe TBS x-ray source for Applied Research

Thanks to R. G. Agostino on behalf of STAR-UNICAL team

Hamamatsu L12161-07

Microfocus X-ray source Hamamatsu L12161-07

Parameter	Value	Unit
X-ray tube voltage setting range	0 to 150	kV
X-ray tube current setting range	0 to 500	µA
X-ray tube voltage operational range	40 to 150	kV
X-ray tube current operational range	10 to 500	µA
Maximum output		
- Small Focus Mode	10	W
- Middle Focus Mode	30	W
- Large Focus Mode	75	W
X-ray focal spot size (Nominal value)		
- Small Focus Mode	7 (5 µm at 4 W)	µm
- Middle Focus Mode	20	µm
- Large Focus Mode	50	µm
X-ray beam angle	Approx. 43	degree
Focus to object distance (FOD)	Approx. 17	mm

Compact Light Source @ Monaco (Germany): Commercially available

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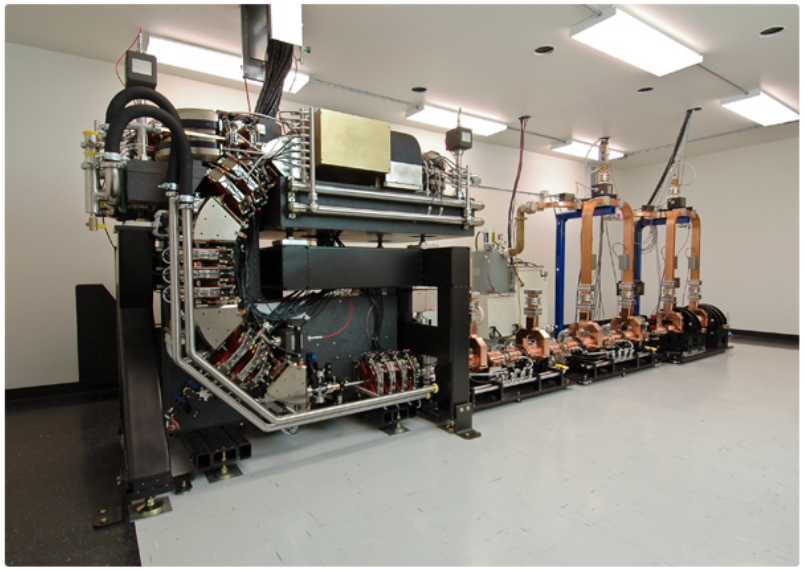
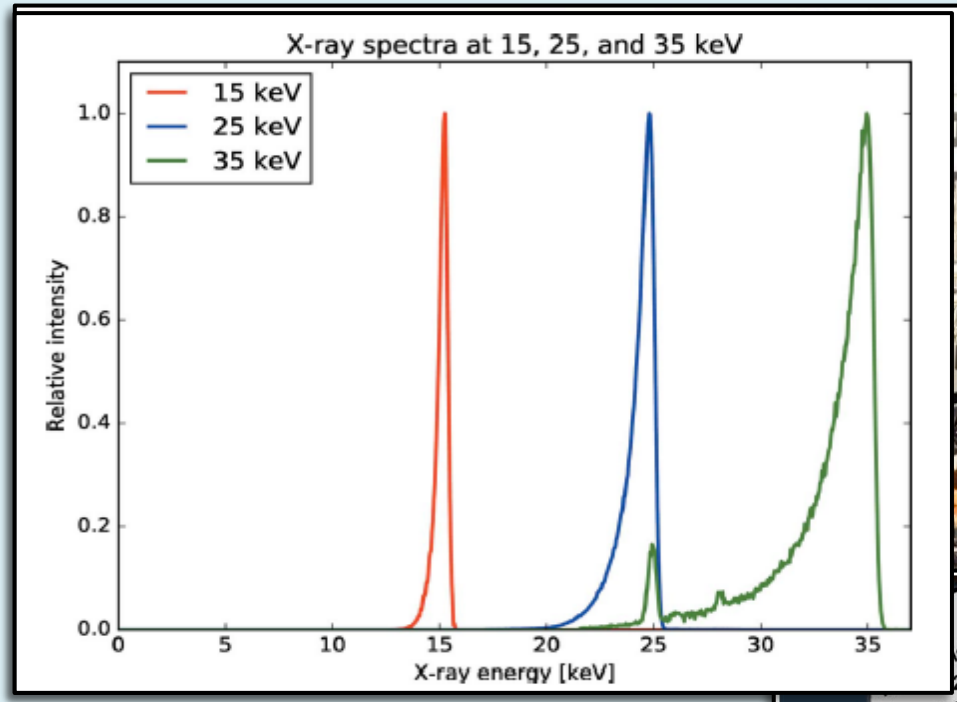
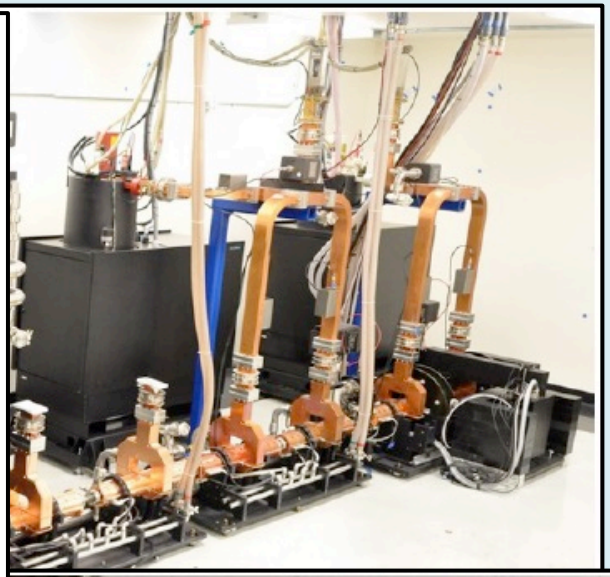
A breakthrough in local, on-demand X-ray synchrotron light

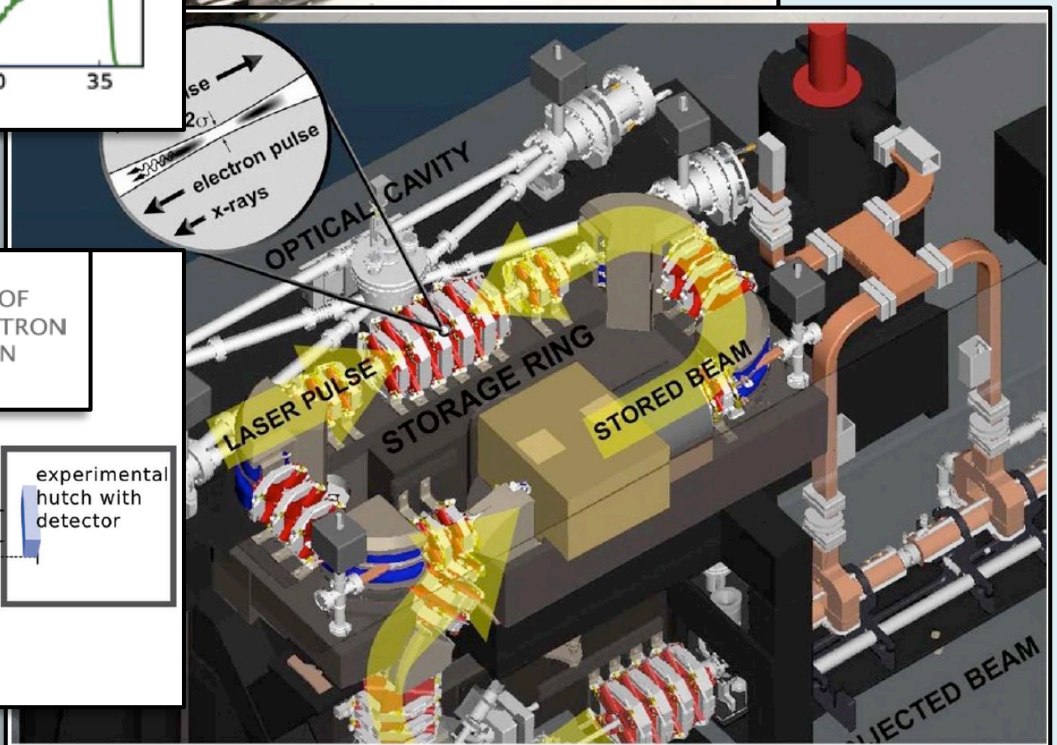


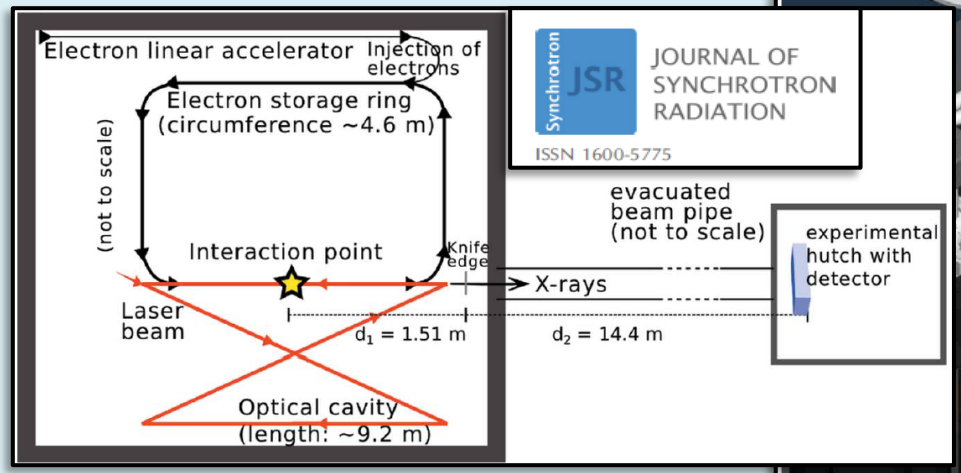
The Lyncean CLS assembled at the headquarters of Lyncean Technologies, Inc. in Palo Alto, CA

Compact Light Source @ Monaco (Germany): Commercially available









Synchrotron JSR JOURNAL OF SYNCHROTRON RADIATION
ISSN 1600-5775

A new interaction chamber scheme 2/3

At realative low energy (as at STAR, 0.5 nC for 60-100 MeV) the focusing channel have to be as compact as possible

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS
8, 072401 (2005)

Adjustable, short focal length permanent-magnet quadrupole based electron beam final focus system

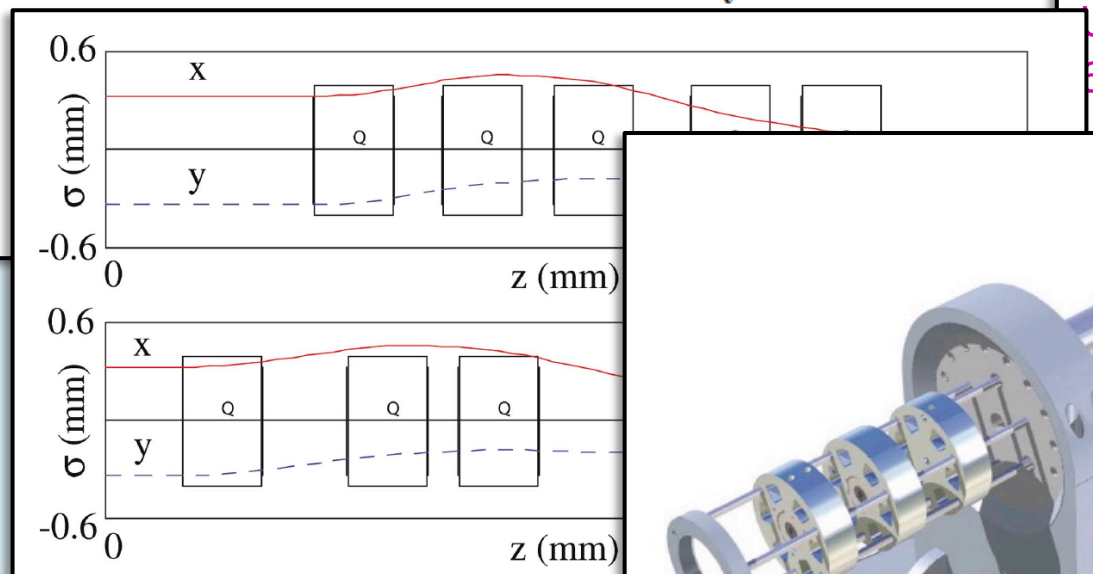
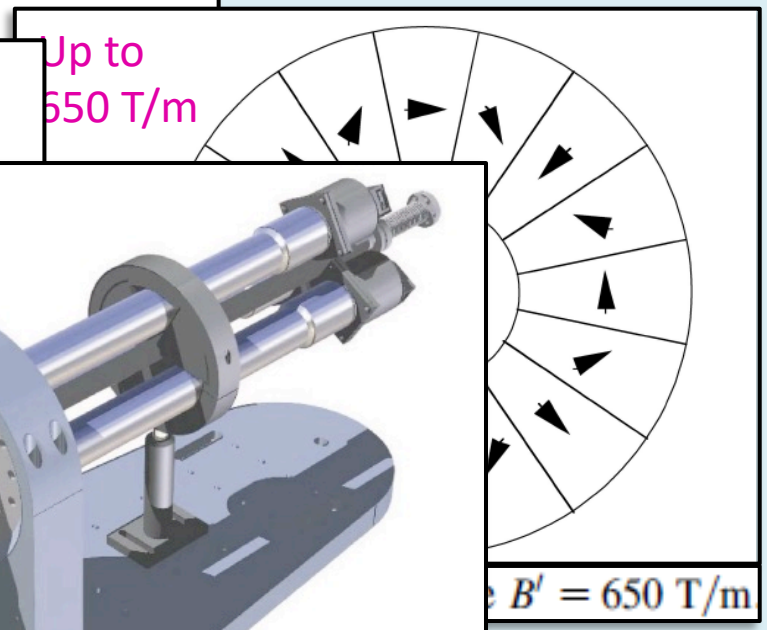


FIG. 8. (Color) Beam energy: 72 MeV (to

072401-11

Up to
650 T/m



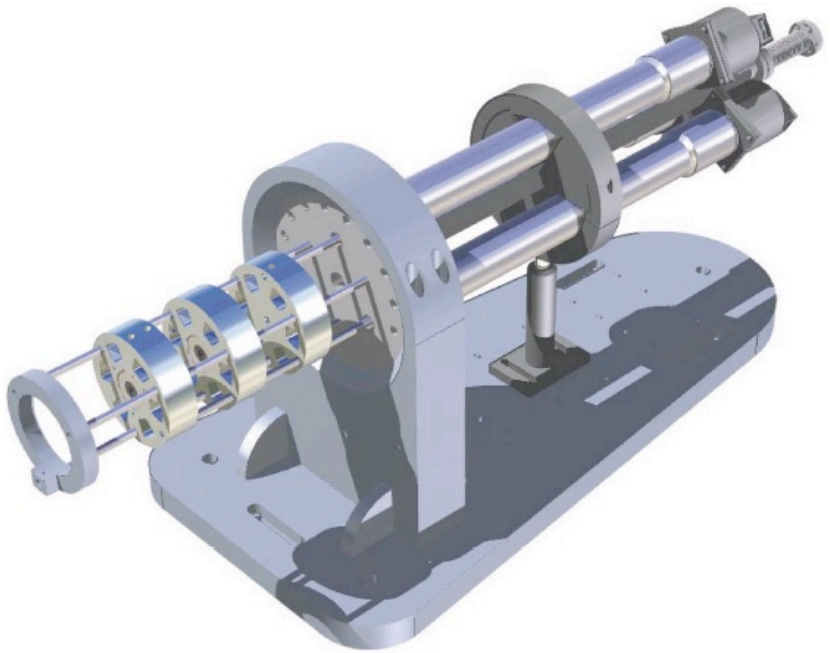
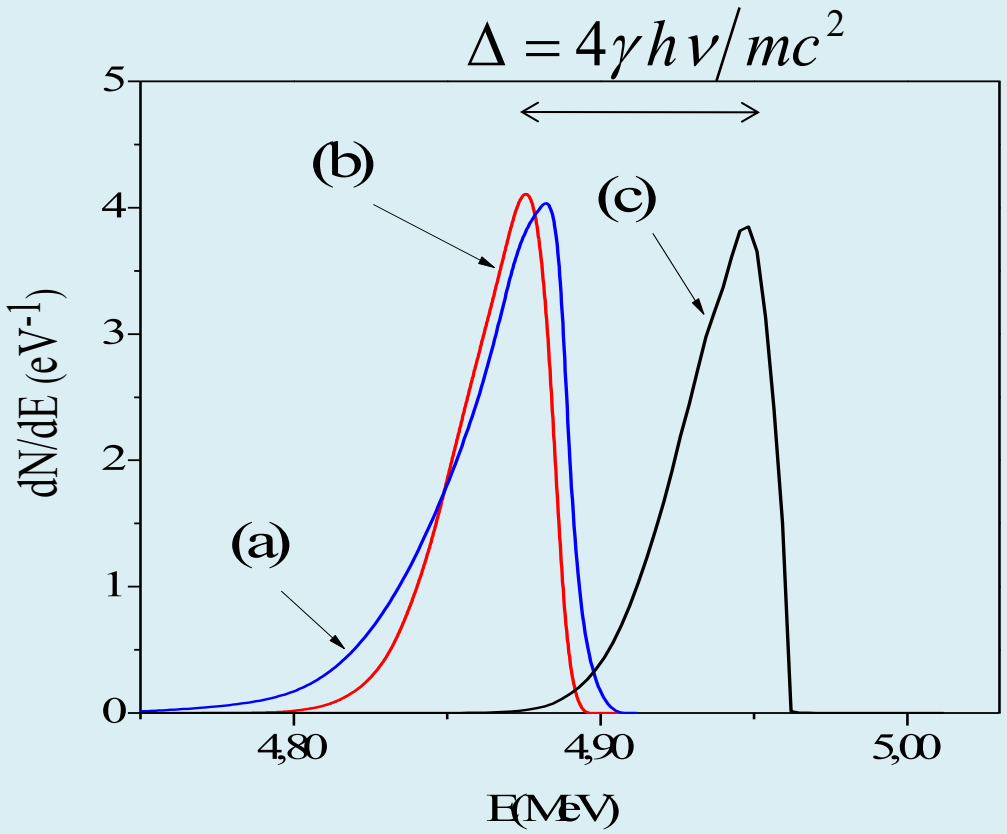


FIG. 14. (Color) Rendered CAD drawing of the final-focus assembly.

Quantum shift ΔE

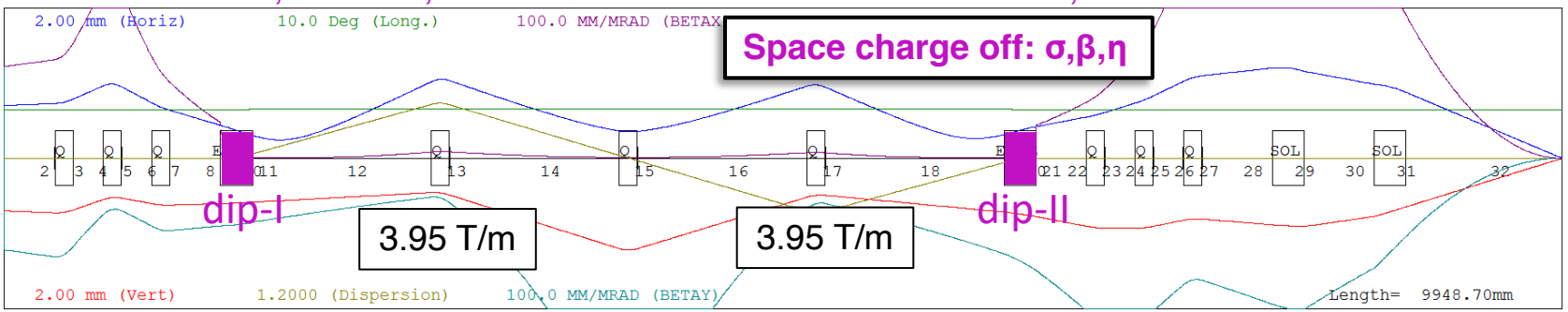


(a)CAIN
(b)Comp_Cross
(c)TSST

A part from the quantum shift, the spectra are very similar

5 m long DogLeg: 20deg for 60 MeV beam

Trace3d Crandall, Kenneth; LA-11054-MS. Los Alamos National Lab., 1987.



Astra http://www.desy.de/~mpyflo/