The Southern Europe Thomson Backscattering Source STAR: Beam Dynamics, Project Status and Foreseen Applications

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

UBA 02-05 July 2019, CANDLE, Armenia

The most effective “photon accelerator”

Inverse **C**ompton **S**ource **VS** Free Electron Laser – “**ICS VS FEL**”

ICS boost twice than an FEL & Further, much shorter undulators!

@ FELs light source 1 Å (12.4 keV) is a typical goal for big infrastructure

FEL

$E_{X\gamma-FEL} \cong 12.4\ keV$

$E_{X\gamma-FEL} = 2\gamma^{2} E_{m.static-und.}$

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

ICS

$E_{X\gamma-ICS} \cong 12.4\ keV$

$E_{X\gamma-ICS} = 4\gamma^{2} E_{laser}$

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

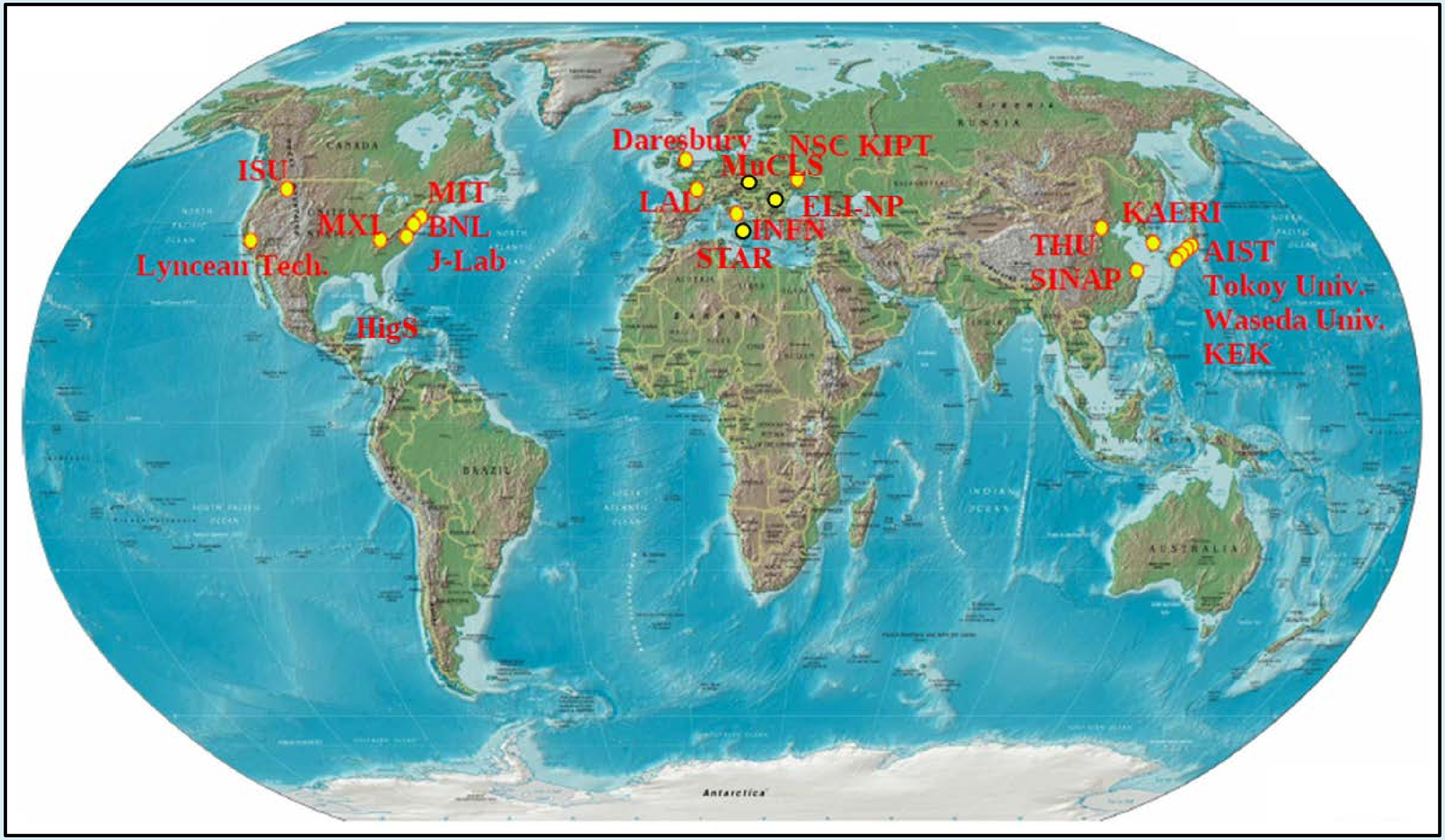
Outline

- Inverse Compton Source (ICS) intro
  1) Worldwide sources
  2) Electron photon ICS laws of scale
  3) Milano group & ICS:
     SPARC_lab, ELI-np (fresh news), STAR

- The **STAR** project: **S**outhern Europe **T**homson back scattering source for **A**pplied **R**esearch

  1) Location & Funds
  2) Beam-line and main characteristics
  3) Beam Dynamics
  4) Interaction Chamber
  5) From Phase-I → to → Phase-II
  6) Foreseen applications (e.g.)

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]	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.

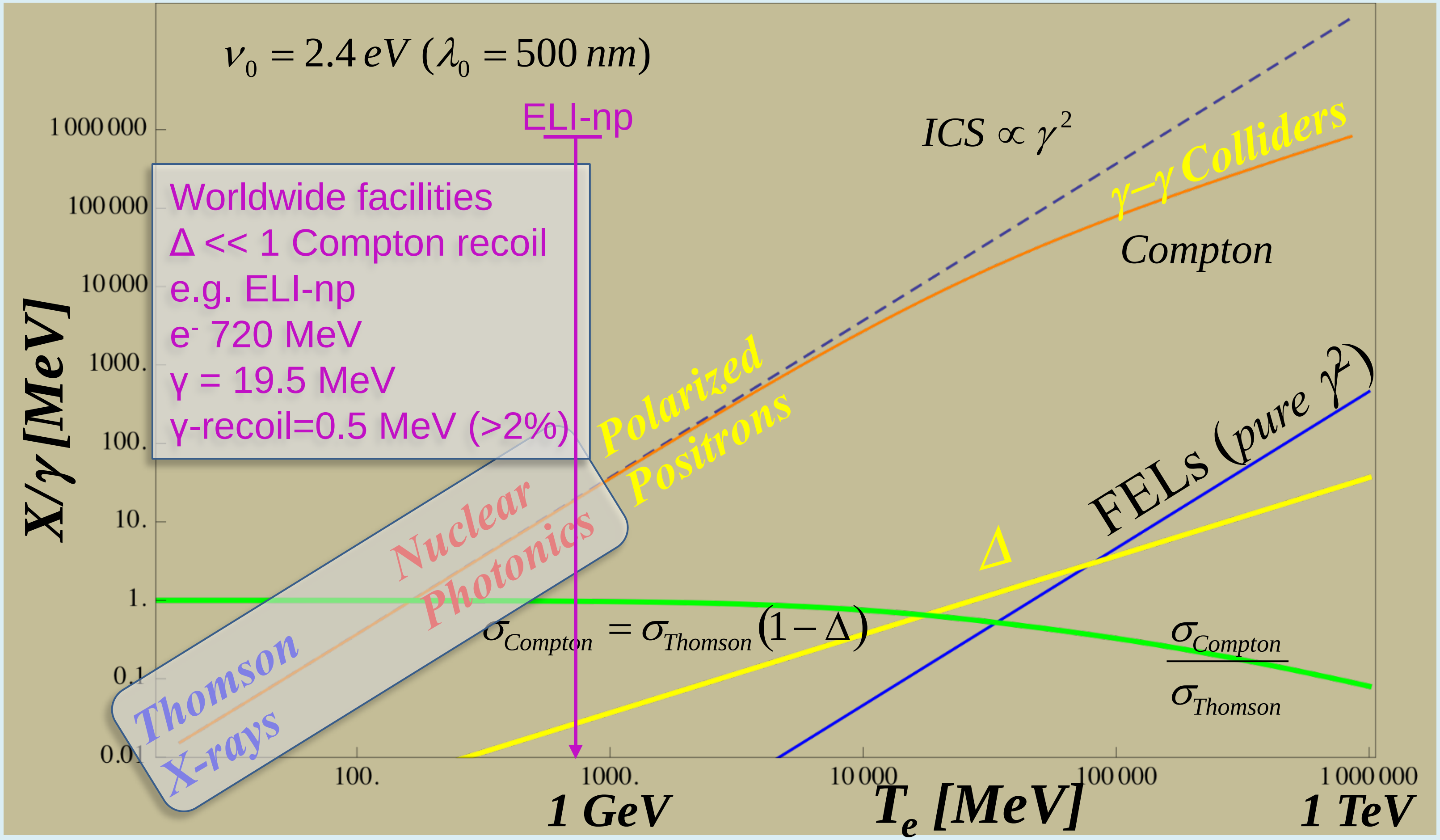
STAR (Calabria)	**Linac**	**20-100**	**10^{10} (100 Hz)**	**18**
ELI-np (Romania)	**Linac**	**0.2-2·10^3**	**10^8 (@ 5‰ bdw)**	**10-30**

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

Electron-photon back-scattering *(3 regimes)*

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

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



BD Milano group & ICS

- STAR @ 20 to 140 keV.
  Electron in next October

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

- **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)=$8 \cdot 10^8$

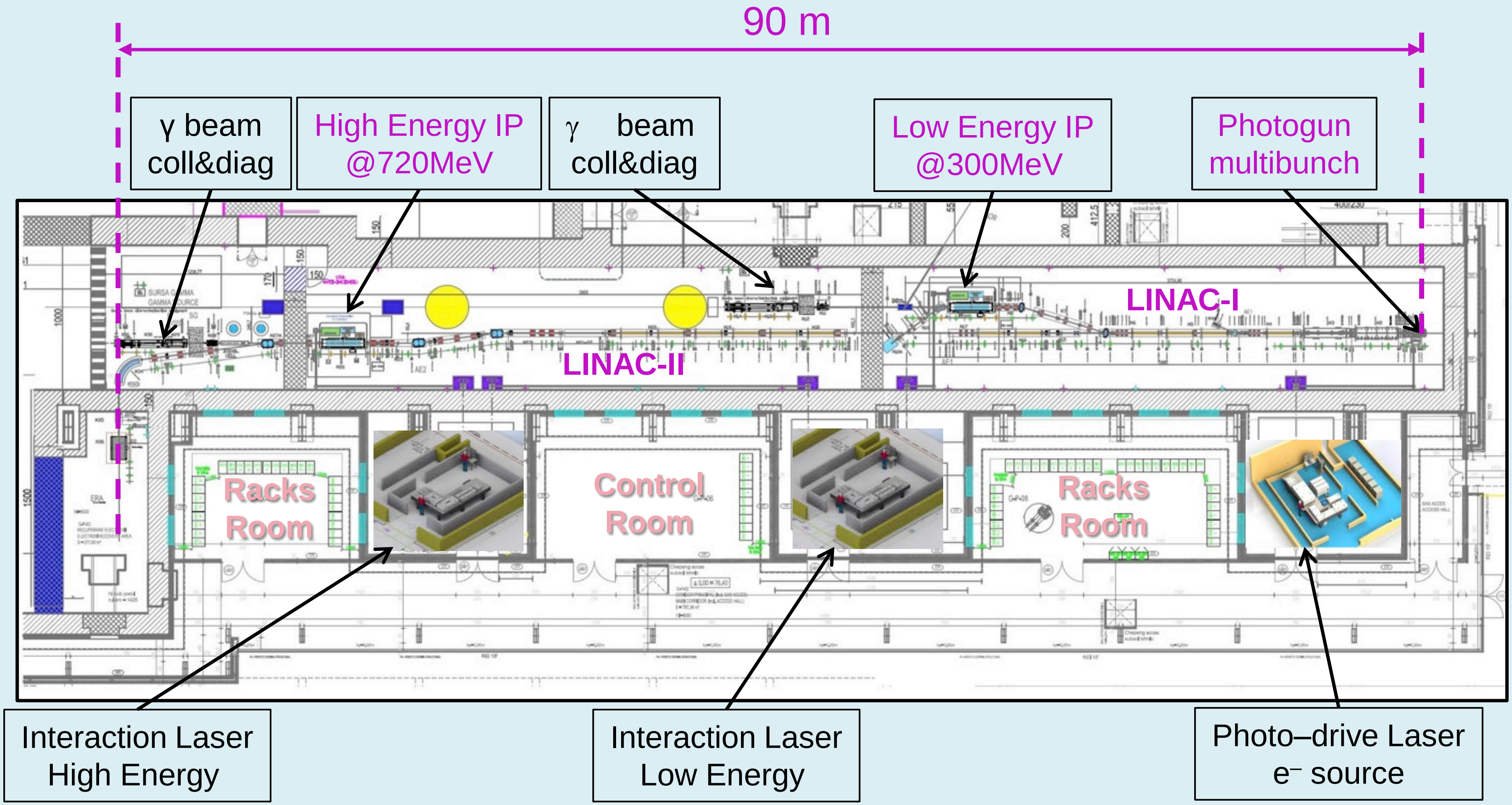
  fresh news

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

Southern europe **T**homson source for **A**pplied **R**esearch

Actors in the project :

Partners

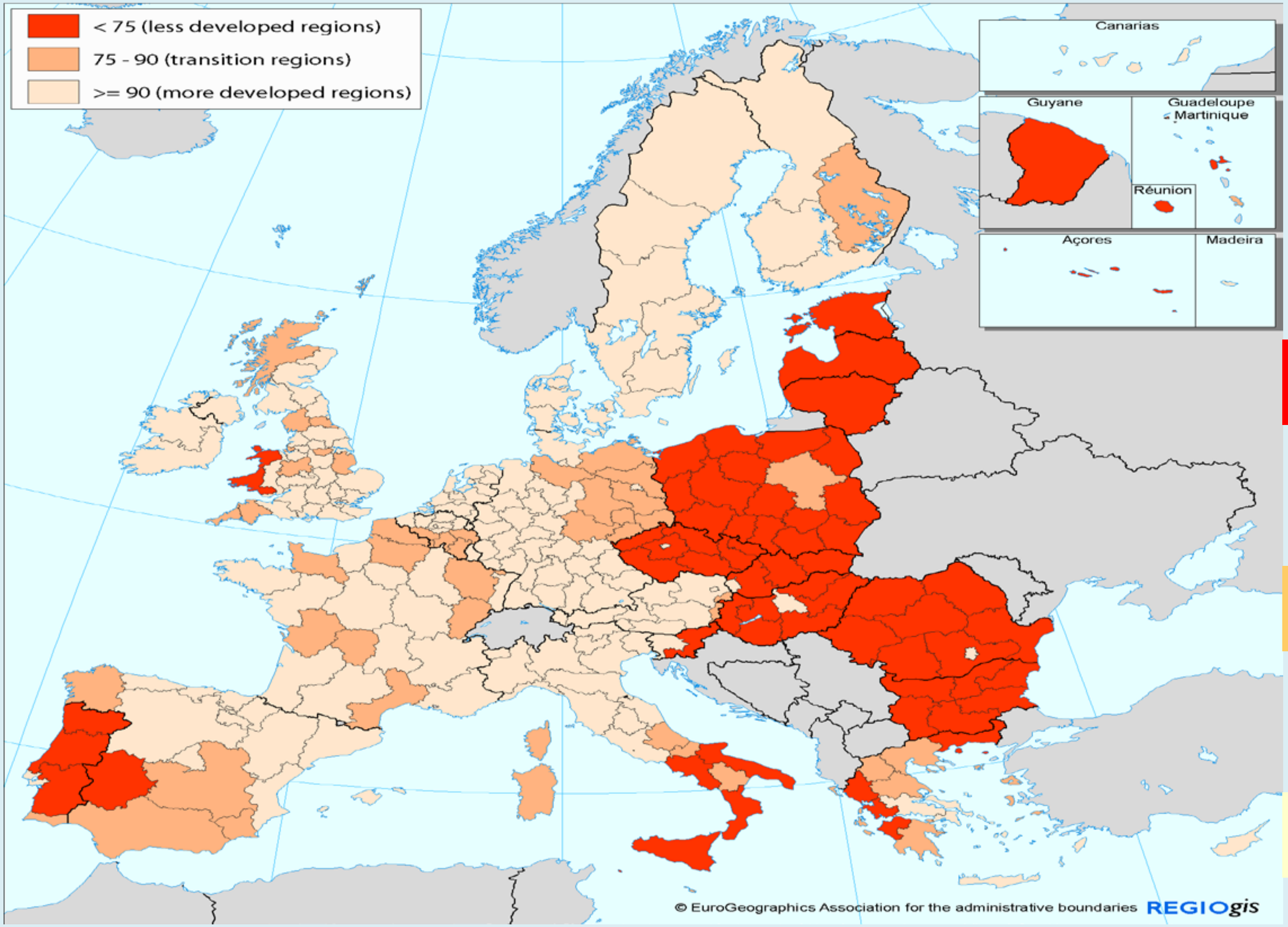
- UNICAL (**UNI**versità della **CAL**abria), machine site
- **CNISM** (**C**onsorzio **N**azionale **I**nteruniversitario per le **S**cienze fisiche della **M**ateria, i.e. Italian Consortium on Physical Sciences of Matter)

Collaborators

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

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**

Location

University of Calabria (UNICAL):
International Architect competition in 1974 (won by Gregotti Bureau), built in 1977

- 35.000 Students
- Strong Physics department

Location & Funds

UNICAL won two PON (founding):

1) Phase I: PON "Ricerca e competitività" 2007 – 2013
   15.7 M€ (~8M for STAR source; ~7M infrastructures)
2) Phase II: PON "Ricerca e Innovazione" 2014 – 2020
   STAR 2.0 - 17.5 M€ - **NOW**

Scientific responsible: Prof. Riccardo Barberi

⇓

The possibility to develop a Linac based research infrastructure, into an University campus. It is really an unique reality in Italy

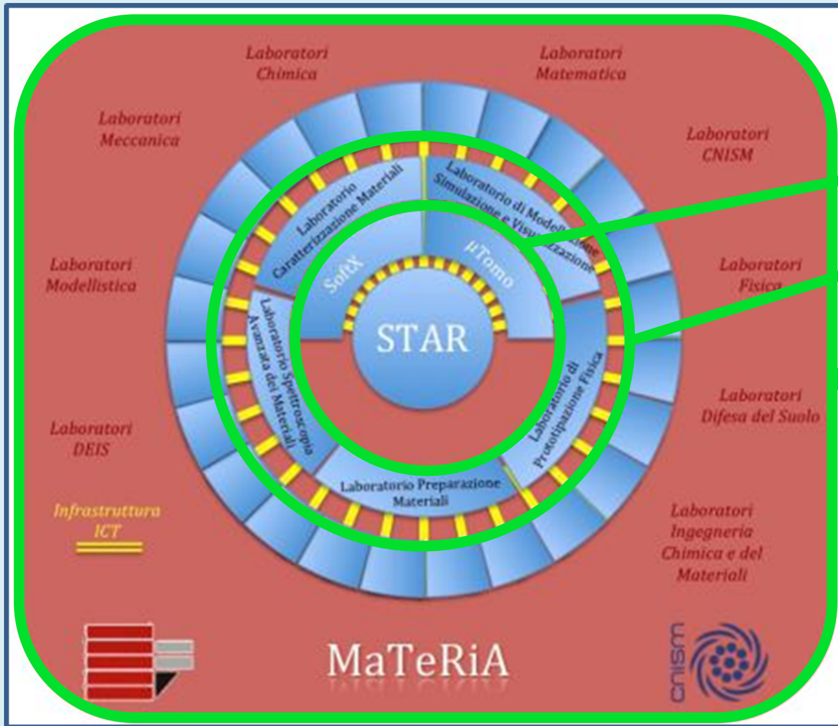
STAR brief description

An **100Hz** ICS **monochromatic** & **tunable** & **ps-long** & **polarized X-ray beam.**

- Phase I (Max. e^- energy 85 MeV): 20 to 140 keV photons
- Phase II (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; …

MaTeRia Infrastructure organized on three layers (**Ma**teriali, **Te**cnologie, **Ri**cerca)



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

First level. **STAR ICS** & **μTomo**

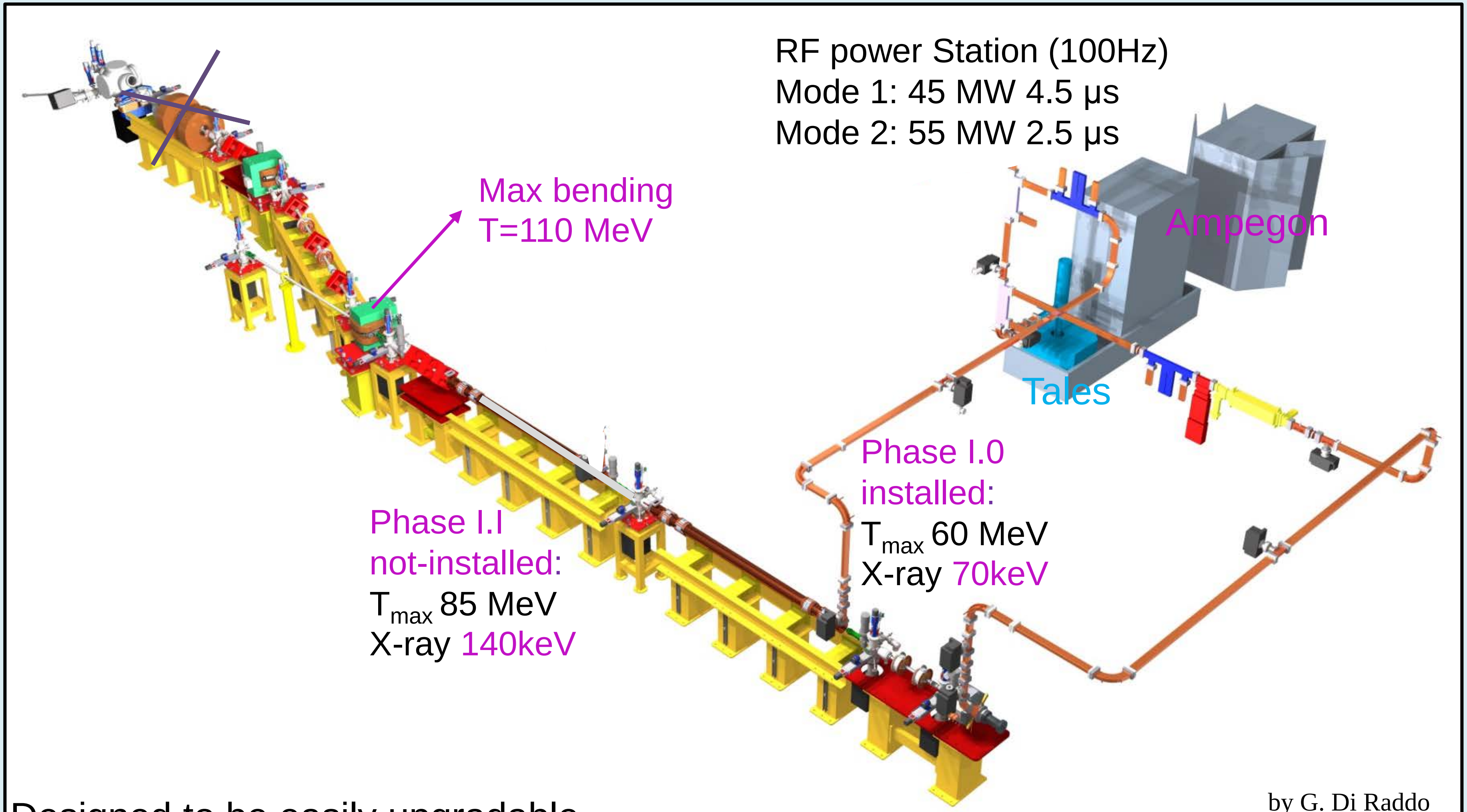
Second level laboratories:

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**

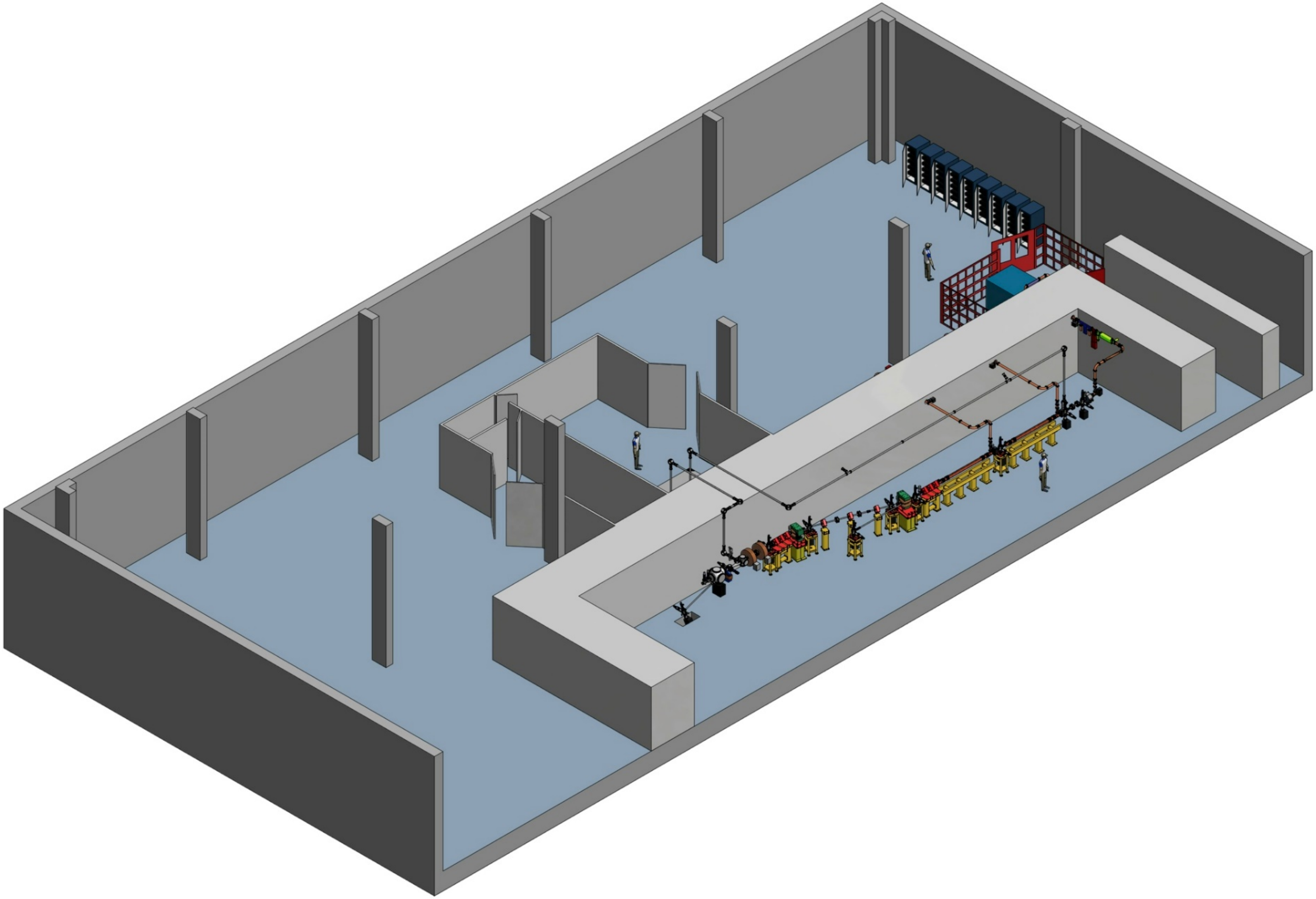
Third level. Network of existent departmental laboratories

R. G. Agostino courtesy

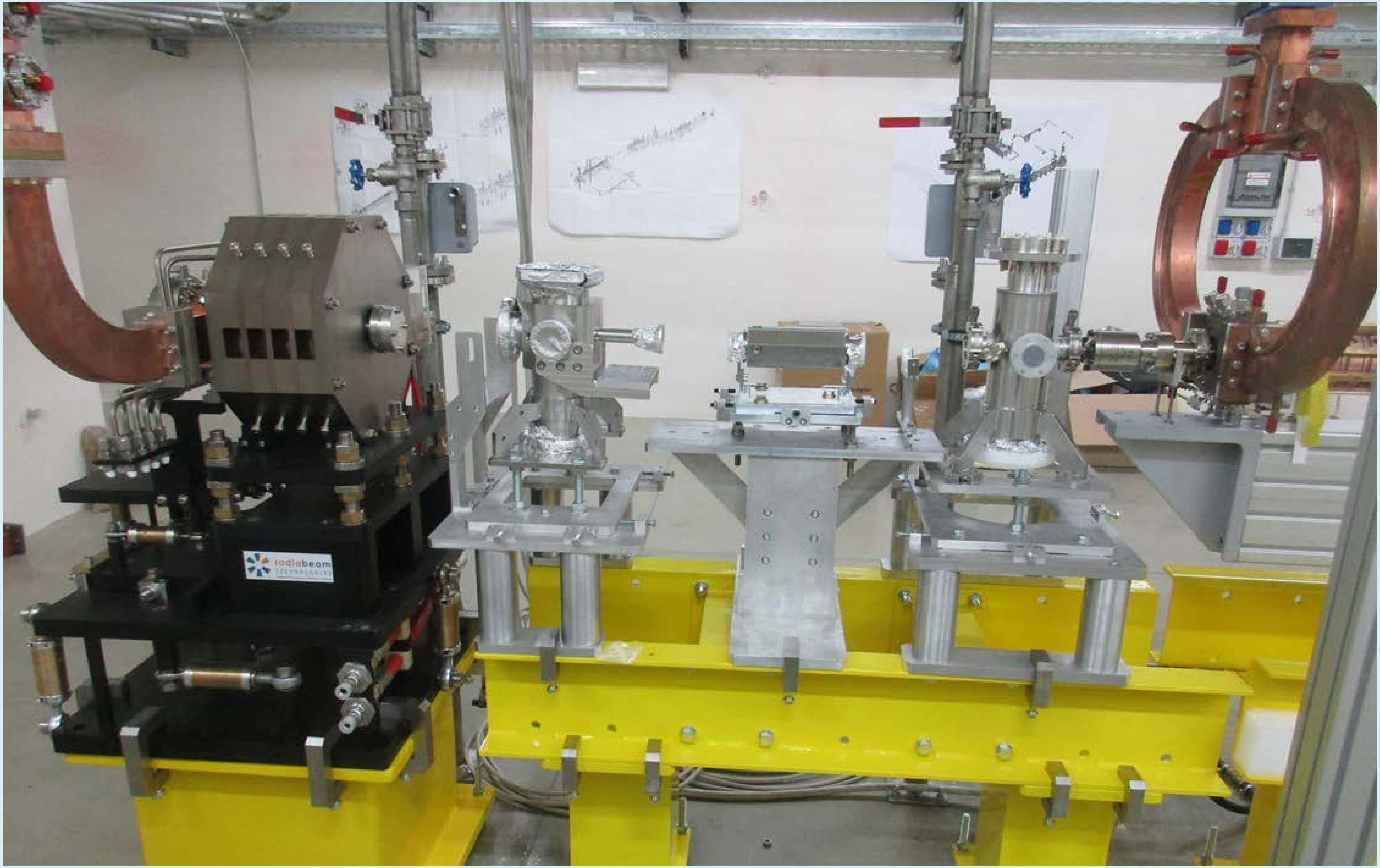
STAR machine layout



Designed to be easily upgradable



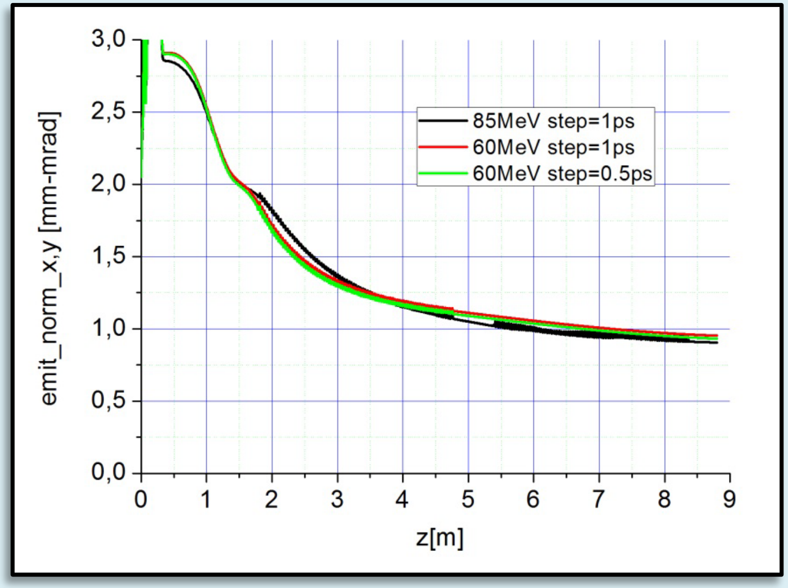
Stato Bunker STAR a Gennaio 2016


radiabeam

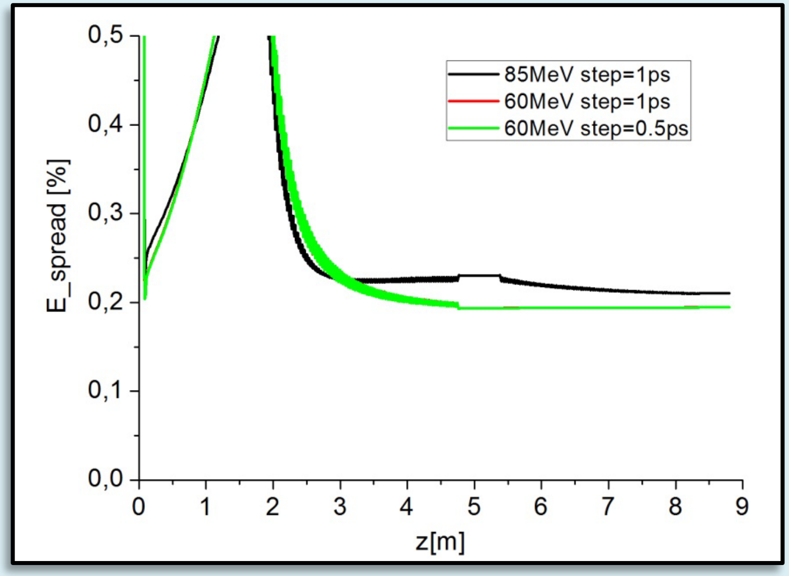
DB linac for the two reference cases: 85MeV and 60MeV

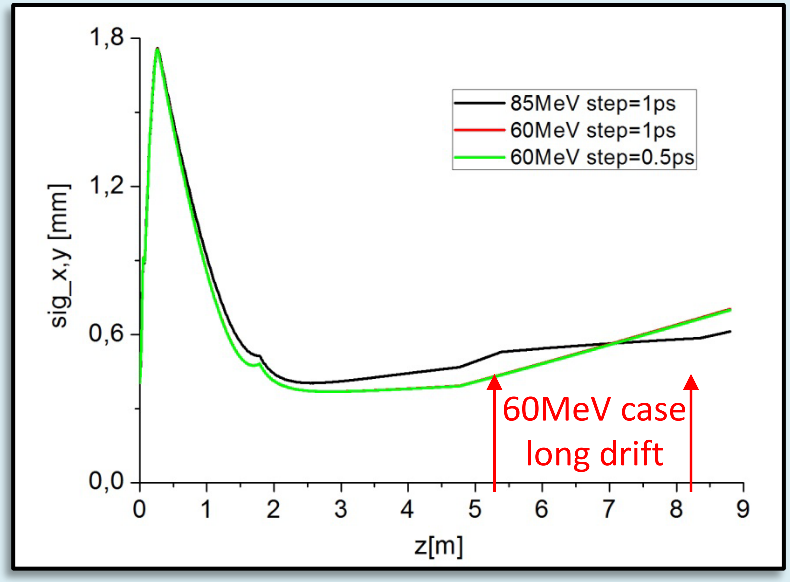
60 MeV – one S-band TW SLAC cavity
Sig_t=3.4ps (Gaussian pulse)
Sig_x=340 μm
Charge=0.5 nC

85 MeV – two S-band TW SLAC cavities
Sig_t=3.7ps
Sig_x=320 μm
Charge=0.5 nC

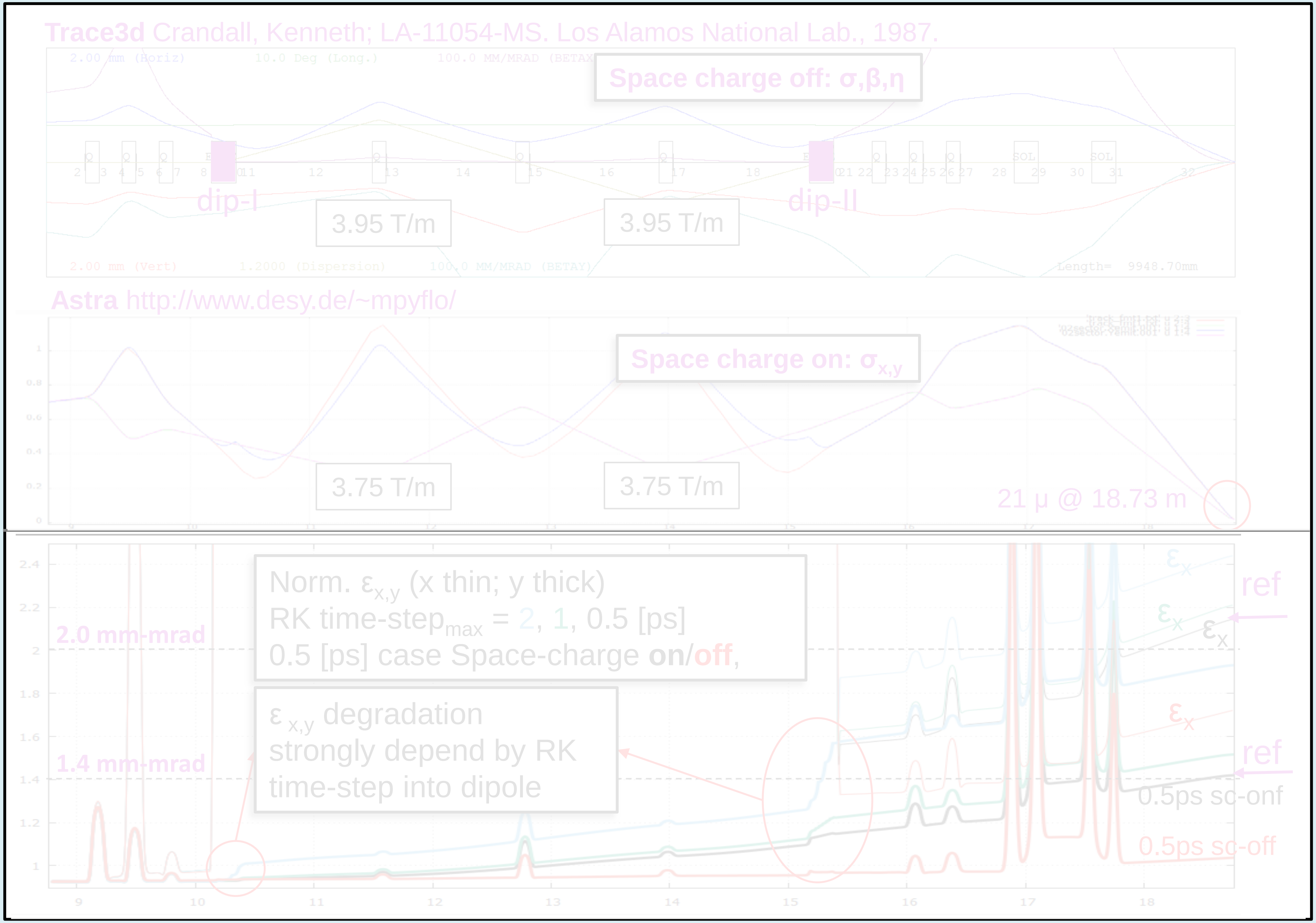


5000mp Astra simulations

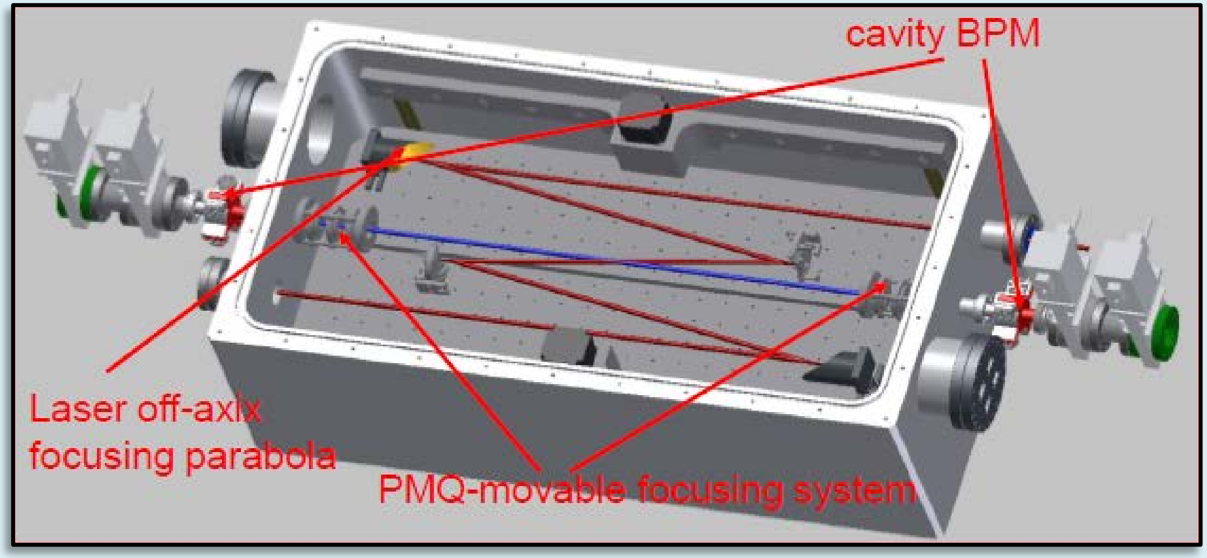




5 m long DogLeg: 20deg for 60 MeV beam



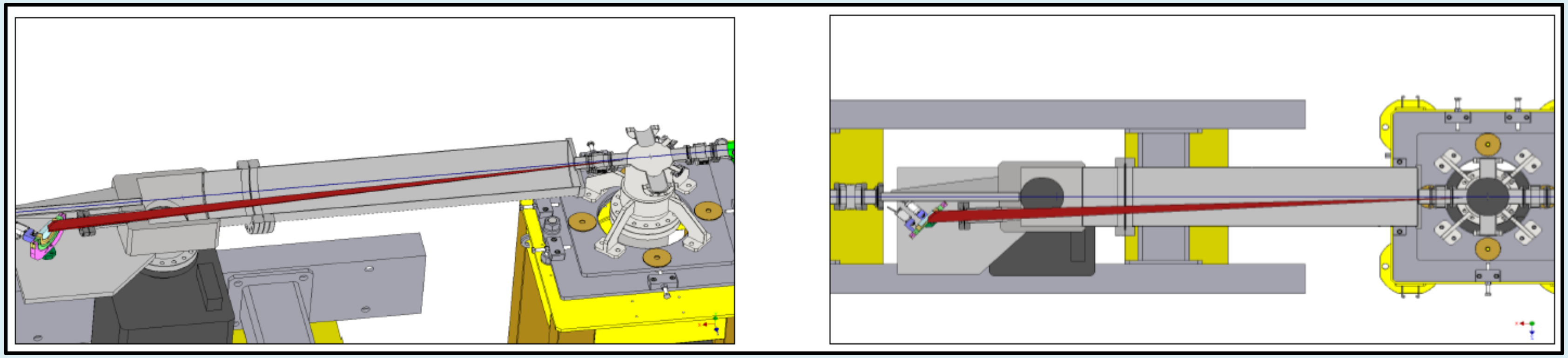
Old & new interaction chamber design



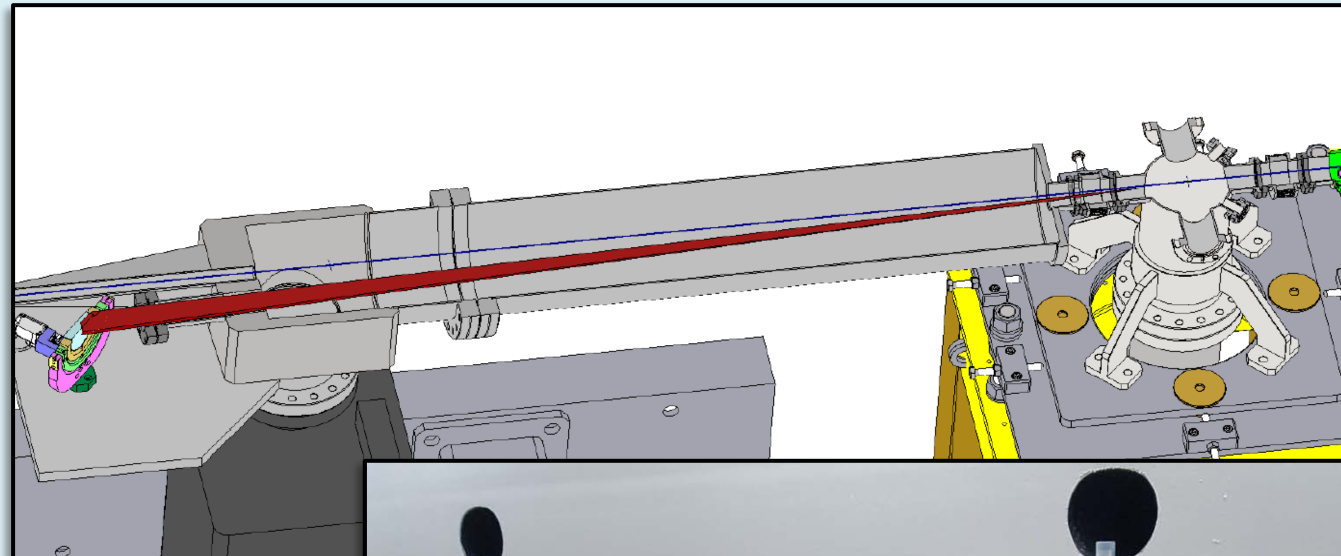
Very expensive: ~ 200k
May be for phase-II

electrons

New scheme: Order of 20k



A diagnostic chamber, with an ad hoc laser entrance
We do not bring out the laser (drawback ?)

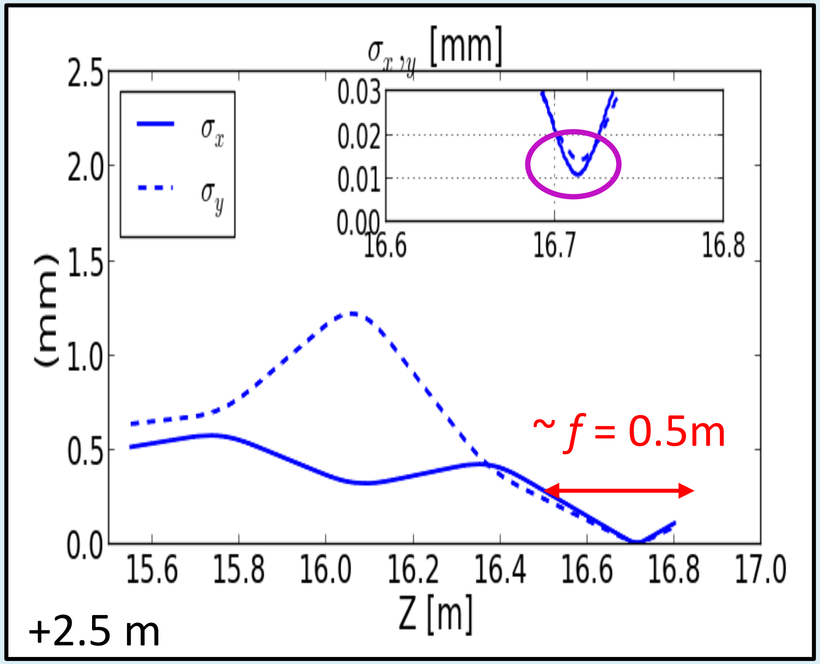



electrons

The Focusing channel

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

Final Fusing Channel



5 m long DogLeg: 20deg for 60 MeV beam

Amplitude, Yb:Yag 100Hz

ps-class laser pulses Reference pulse lenght: 2 ps

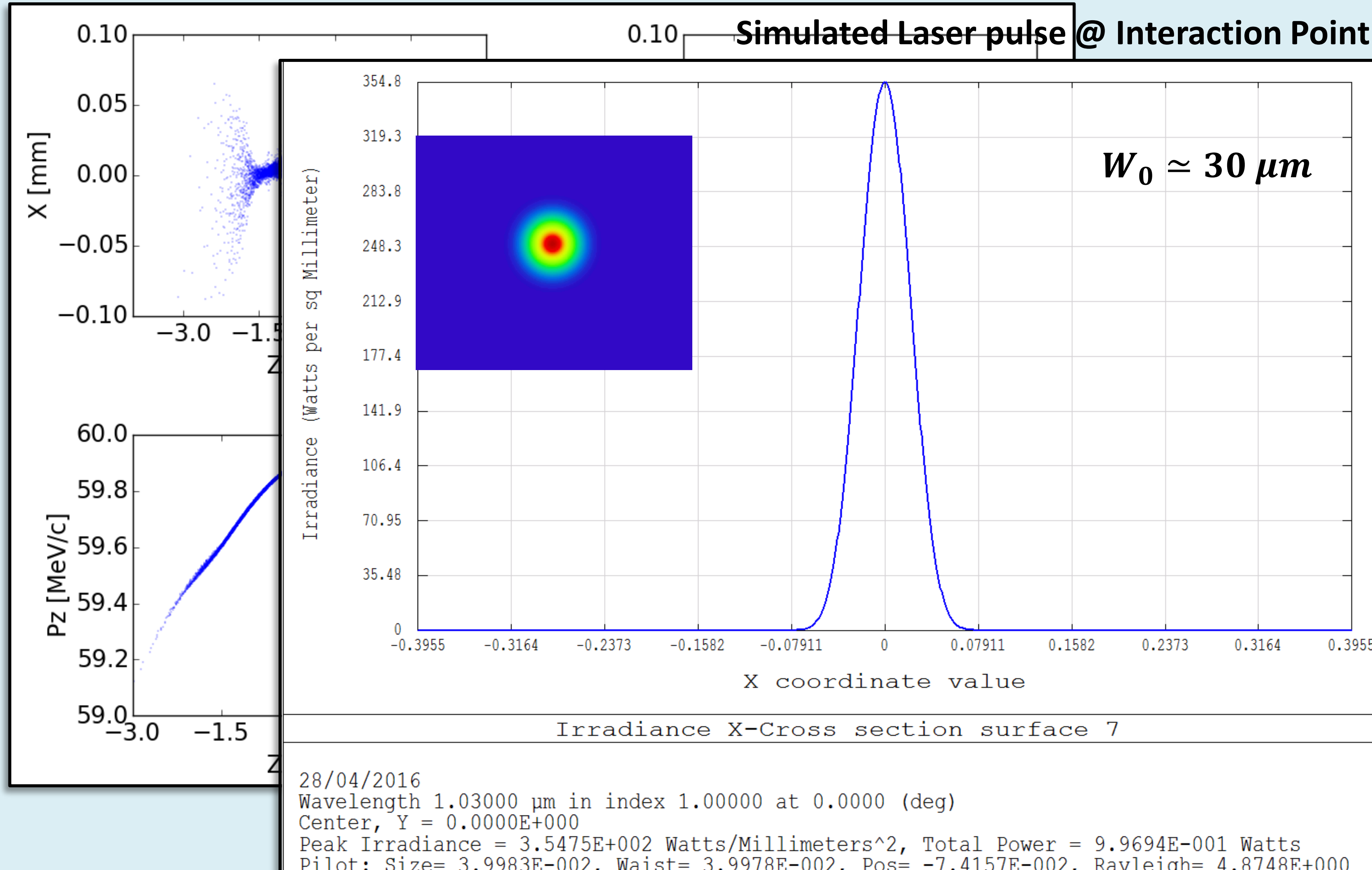
Lasers spec (some values can change)

	Photocathode laser Phase 1	Interaction laser Phase 1	Interaction laser Upgrade phase 2
Repetition rate (Hz)	100	100	100
Output Energy (mJ)	>0,3	130 **NOW**	~1000 **Phase 2**
Short term energy stability (% rms)	<1	<1	<2
Long term energy stability (% peak-peak)	<2	<3	<5
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

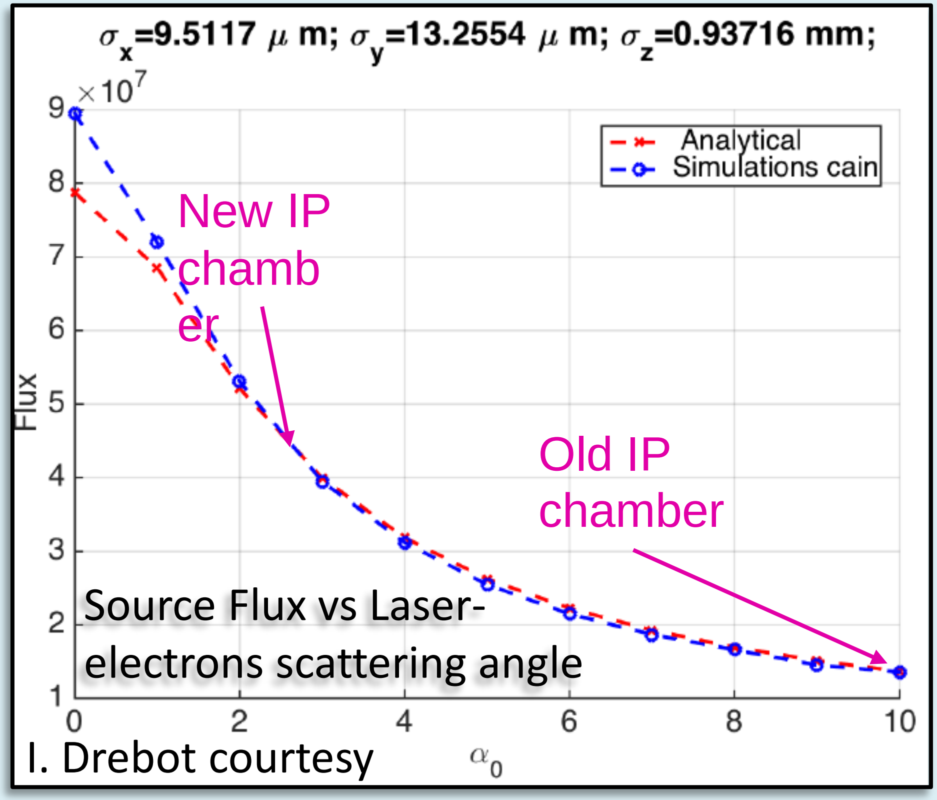
Source performances 1/2

Simulated Electron Bunch @ Interaction Point

Simulated Laser pulse @ Interaction Point



Source performances 2/3

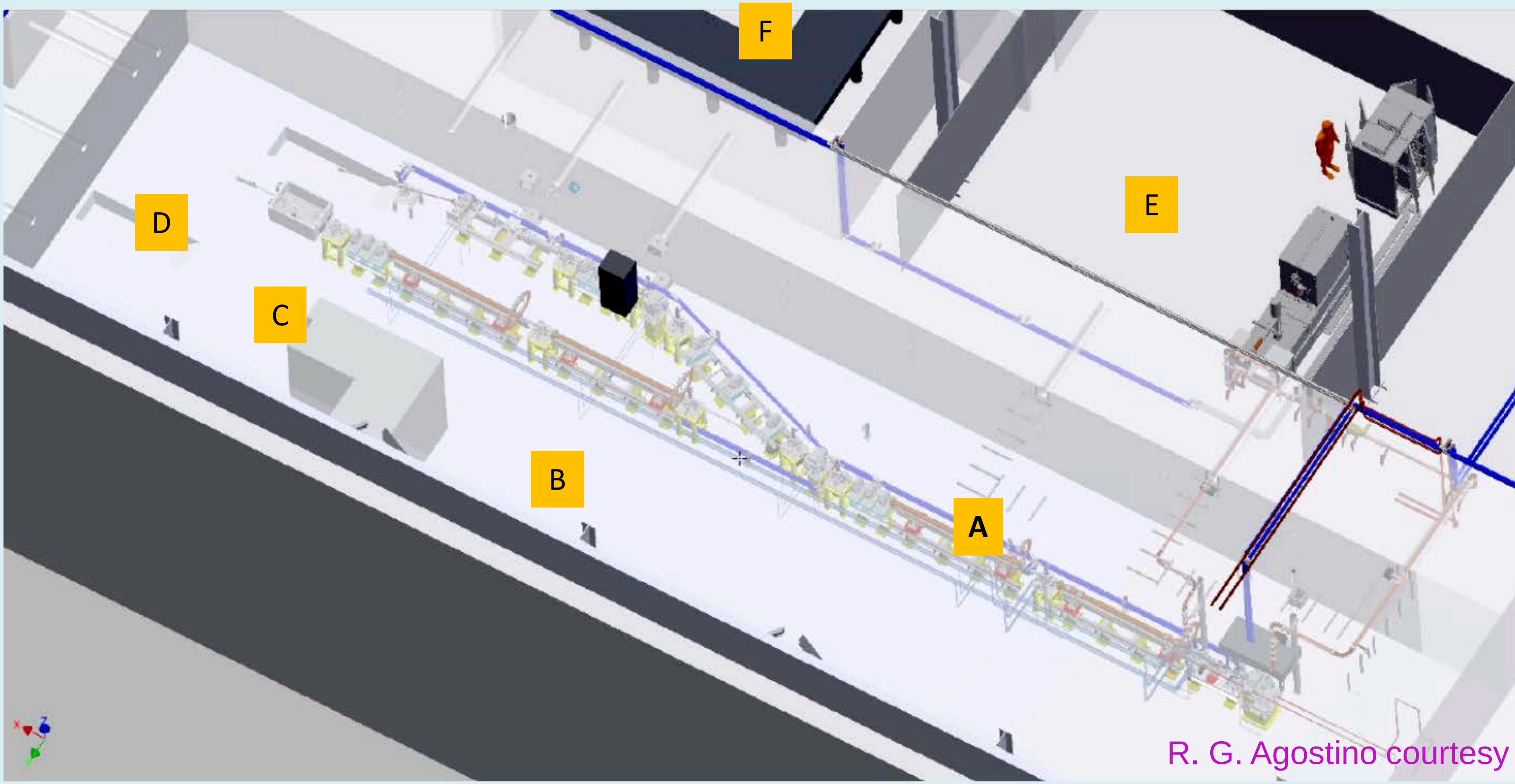


- Old IP chamber α_{IP} = 10°
- New IP chamber α_{IP} = 2.3° (here α_{IP} = 3° , to be conservative)

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

DB simulations for Phase II are not still available

STAR phase II



STAR UPGRADE PHASE-II (60 → 190 MeV)

A. 2nd SLAC-type LINAC
B. High Energy branch «STAR-HE-Linac» (2 LINAC system)
C. Impact chamber
D. Beam dump
E. 2nd S-band RF power station
F. Upgrade laser system

STAR phase-I

STAR operating modes:

- **high-flux** → Medical imaging;
- **moderate-flux / monochromatic mode** → Better detection/dose performance;
- **short-and-monochromatic** → Pump-and-probe experiments.

Operating modes	High-flux	Small-BW	Short-pulse
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)	[illegible]	[illegible]	[illegible]

ICSs linac driven
are **easily tunable**
and **easily upgradable**

STAR phase-II

	STAR-HE	STAR-LE
Photon energy (keV)	**70-350 (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

Existing USER mainly from UNICAL Departments & established 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)

Foreseen applications

around 20 keV → mammografy in phase contrast

ELSEVIER

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

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

30-8

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

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

Calabria: rich in archaeological sites and finds

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

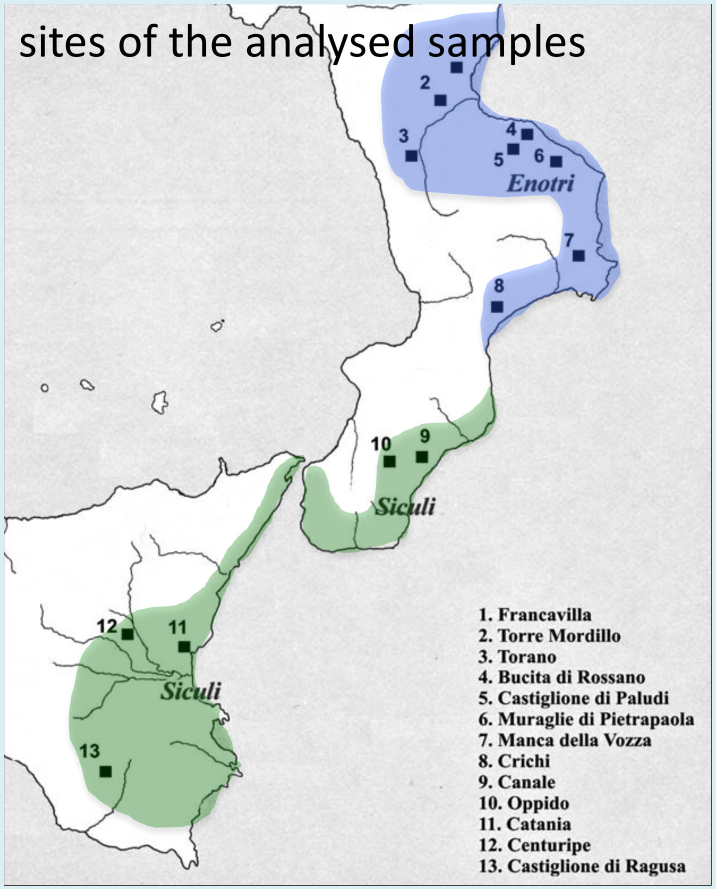
PEACE SYMBOLS IN CALABRIA BEFORE GREEK COLONIZATION (A preliminary study @ STAR μTomo)

type-A

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) and type-B (2 findings)



stribuzione dei pendagli a coppia antropomorfa.

STAR Southern Europe TBS x-ray source for Applied Research

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

Goal of the STAR µTomo study

- **Chronological order** and evolution

- **Production techniques**: alloy melting and removal/addition.

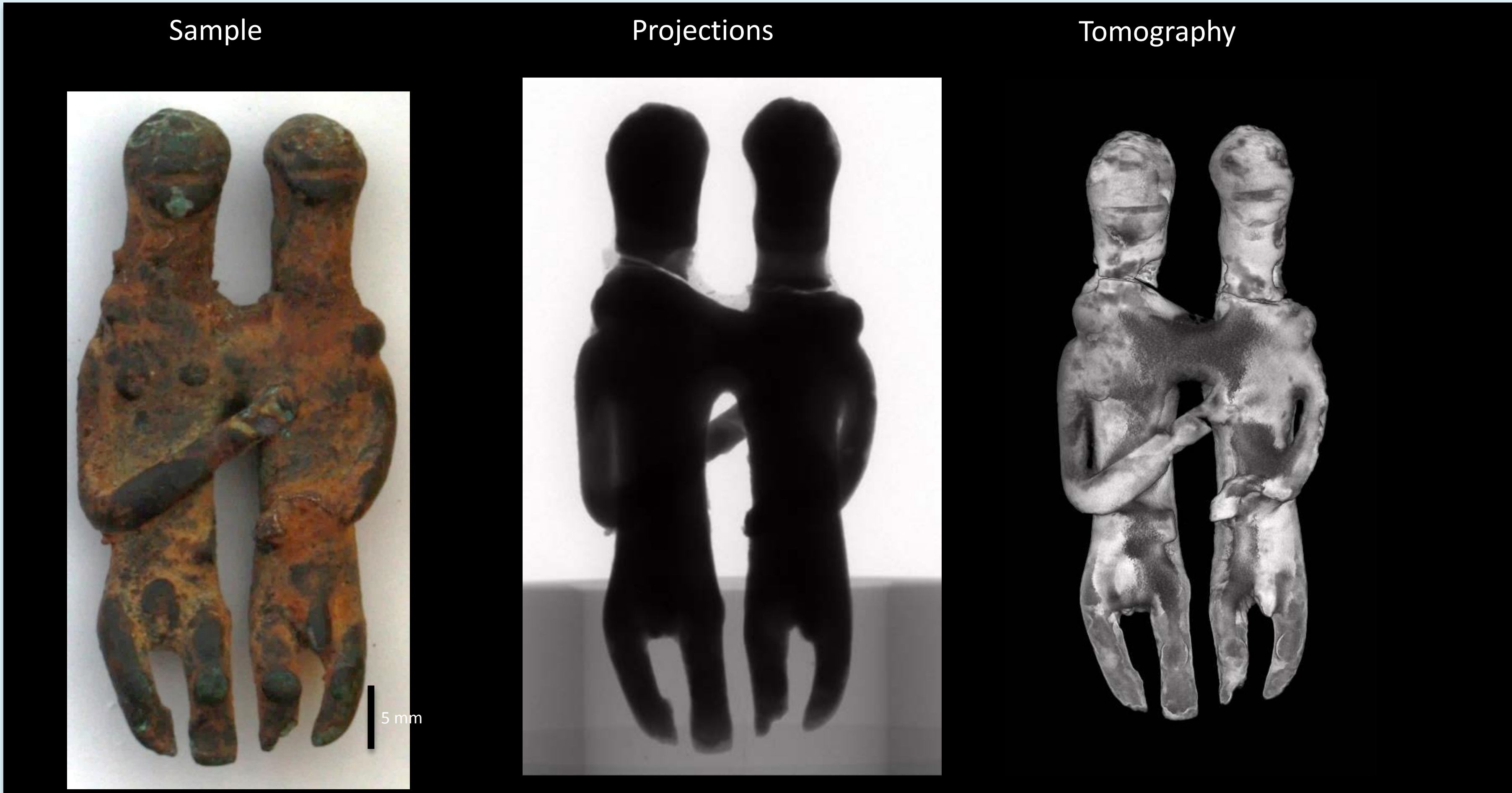
- **Production site** : Compare finds from different sites and different cultural.

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

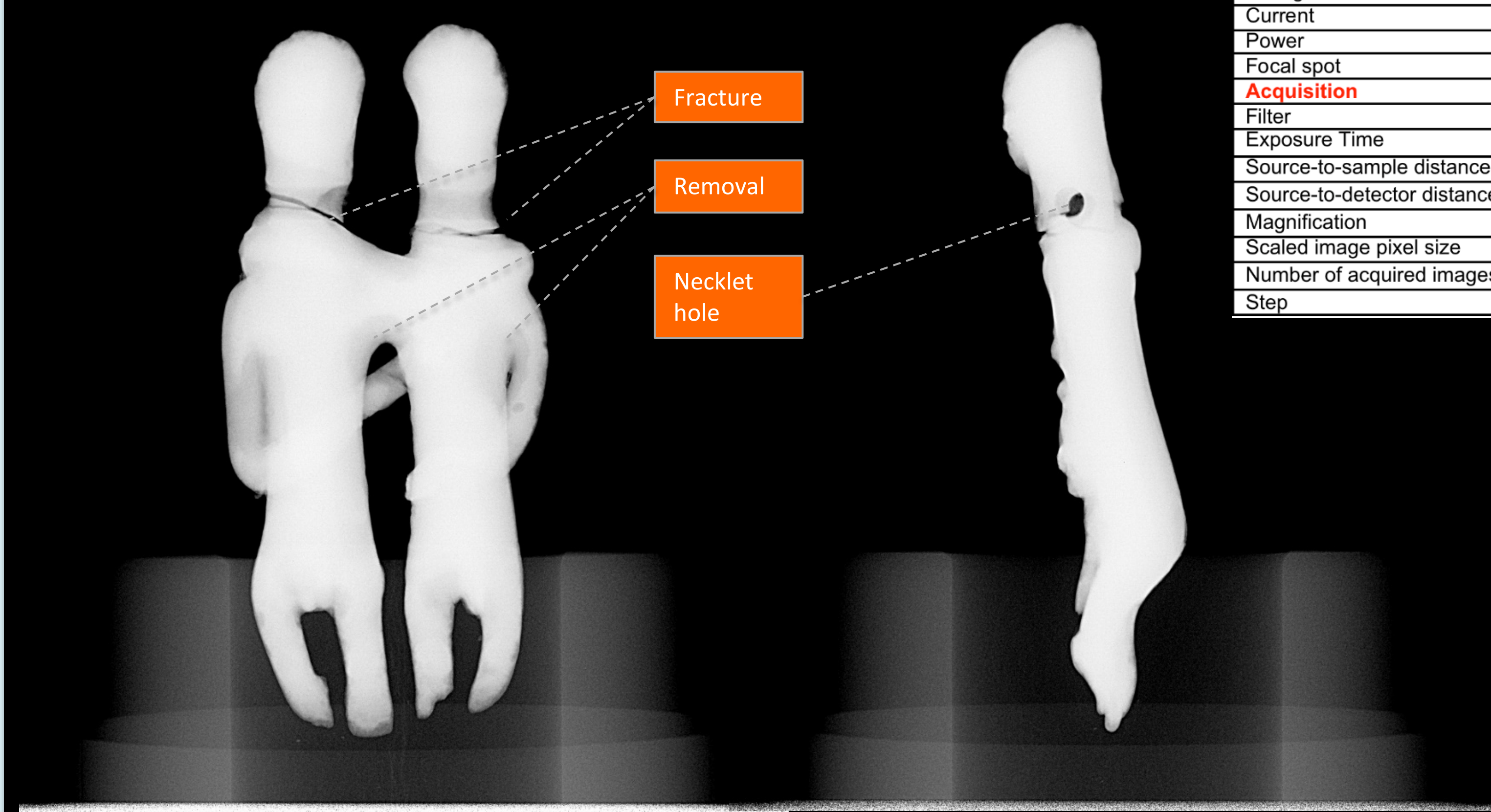
Results: X-ray micrography



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

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

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

Layout: X-ray microtomography@µTomo experimental station

STAR

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

PEACE SYMBOLS: preliminary results

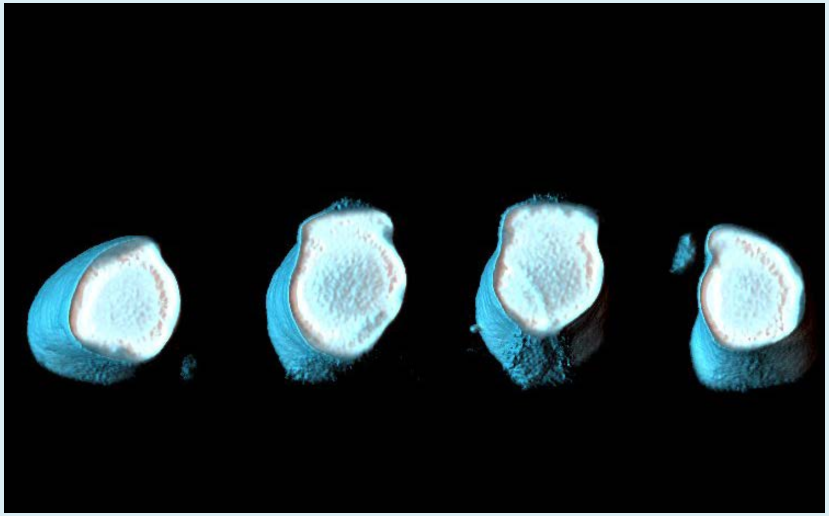
Type A

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

Type B

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

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



Presence of additions on the knees

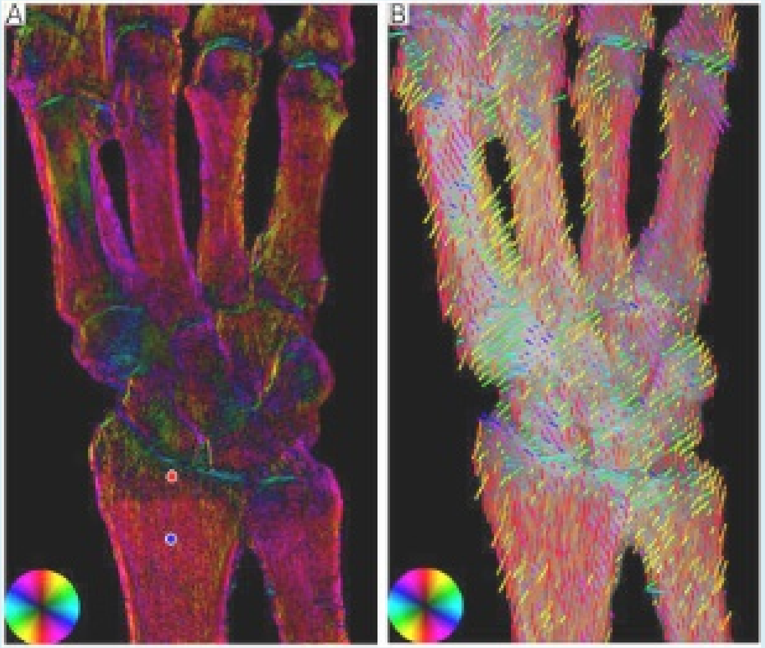
STAR
Southern Europe TBS x-ray source for Applied Research
Thanks to R. G. Agostino on behalf of STAR-UNICAL team

Conclusions

ICS in the last few years, by simulations **&** recent experimental results have shown great benefits in more fields.
Furthermore,
Synchrotron needs huge infrastructures to reach 100keV x-ray
ICS can reach very high e… €

Thanks for
your attention

Waiting to TURN-ON STA…
snooping @ Munich CLS. First Commercially available ICS (Lyncean tec. - USA)



"Trabecular bone anisotropy imaging …", C. Jud at al. Scientific Reports 7, 14477 (2017)

↓

Microfractures that are often missed in classical radiographs

BD Milano Group

Luca Serafini
Vittoria Petrillo
Alberto Bacci
Andrea Renato Rossi
Illya Drebot
Marcello Rossetti Conti
Marcel Ruijter
Michele Opromolla

Compact Light Source @ Monaco (Germany): Commercially available

lynceantech.com/products/

lyncean TECHNOLOGIES, INC.

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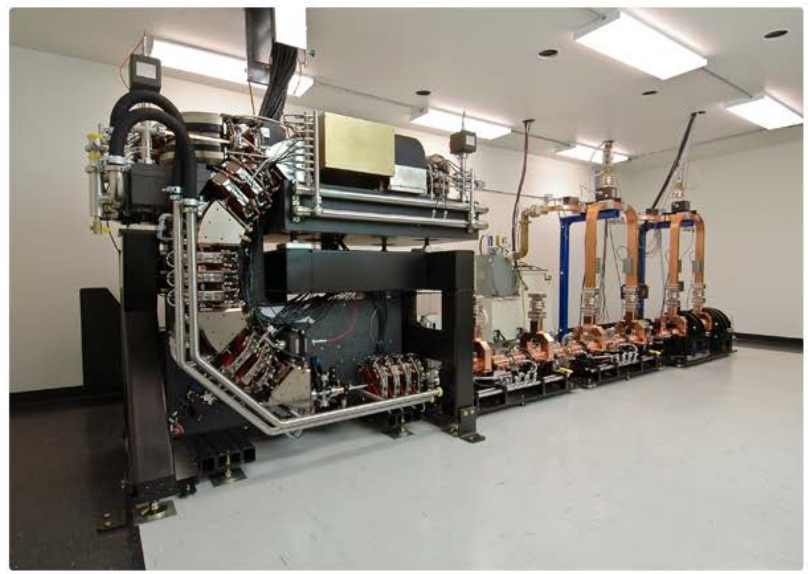
HOME > PRODUCTS

illuminating X-ray science™

- **Compact Light Source**
- Compact X-ray Station

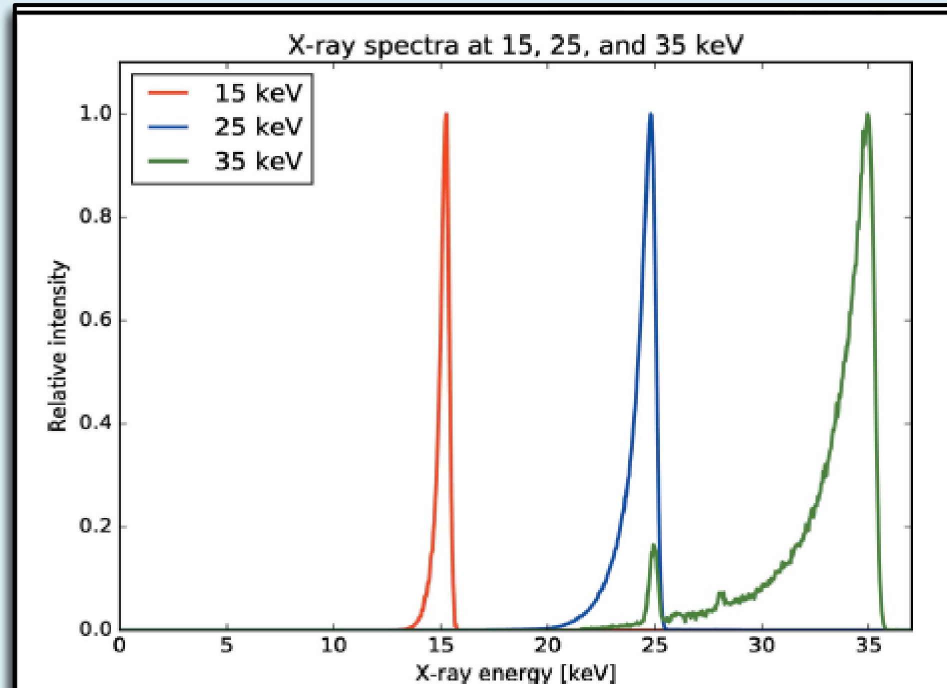
THE LYNCEAN COMPACT LIGHT SOURCE (CLS)

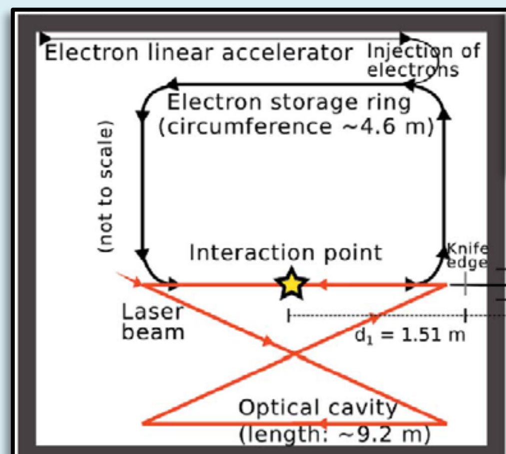
A breakthrough in local, on-demand X-ray synchrotron light



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

Compact Light Source @ Monaco (Germany): Commercially available





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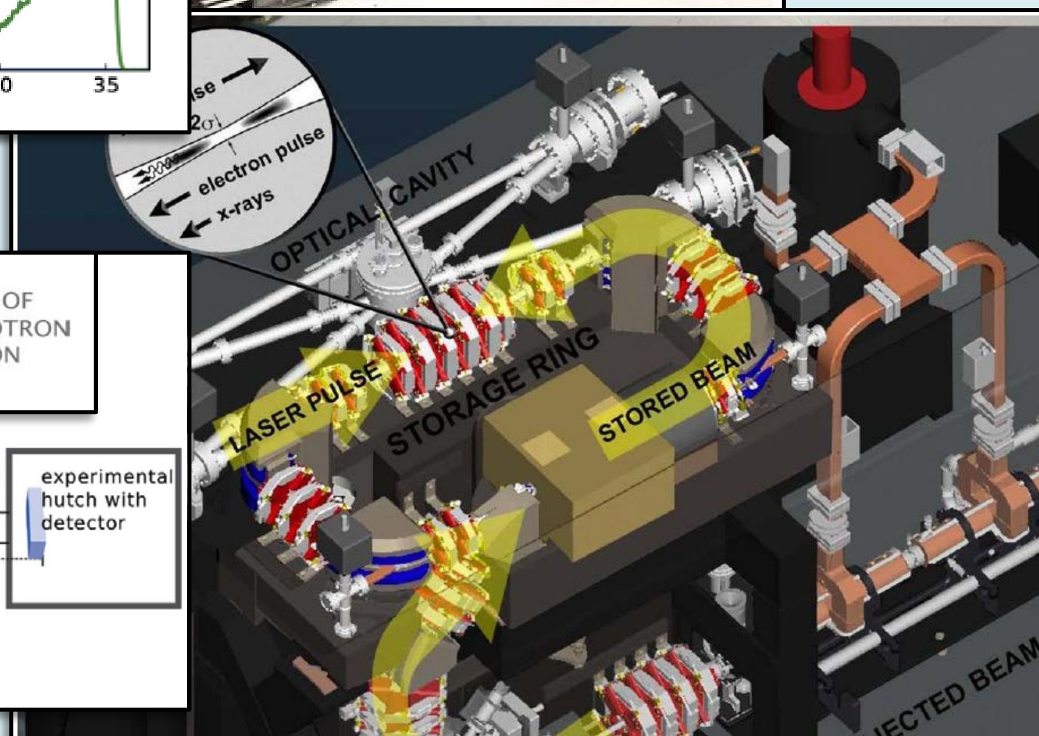
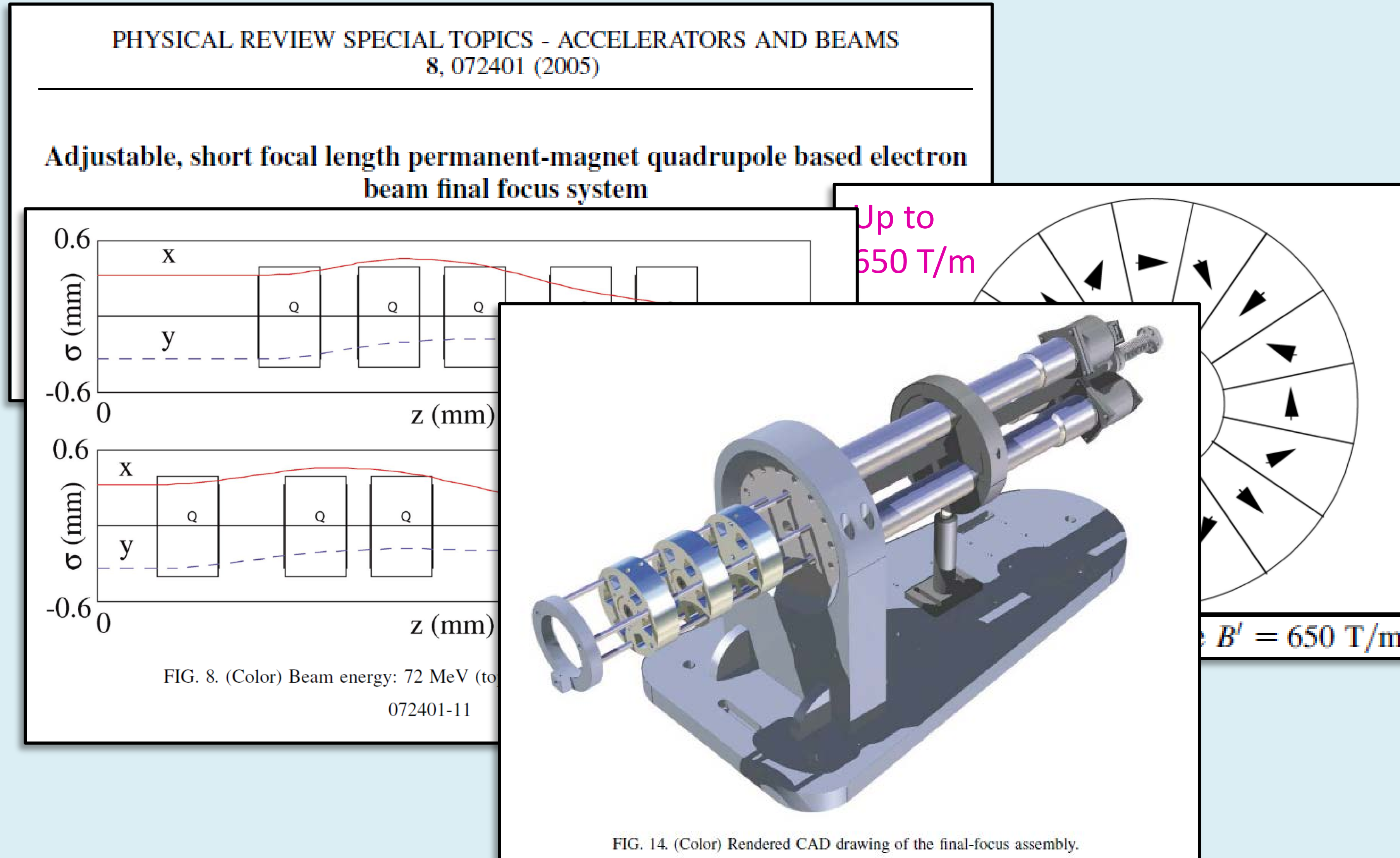


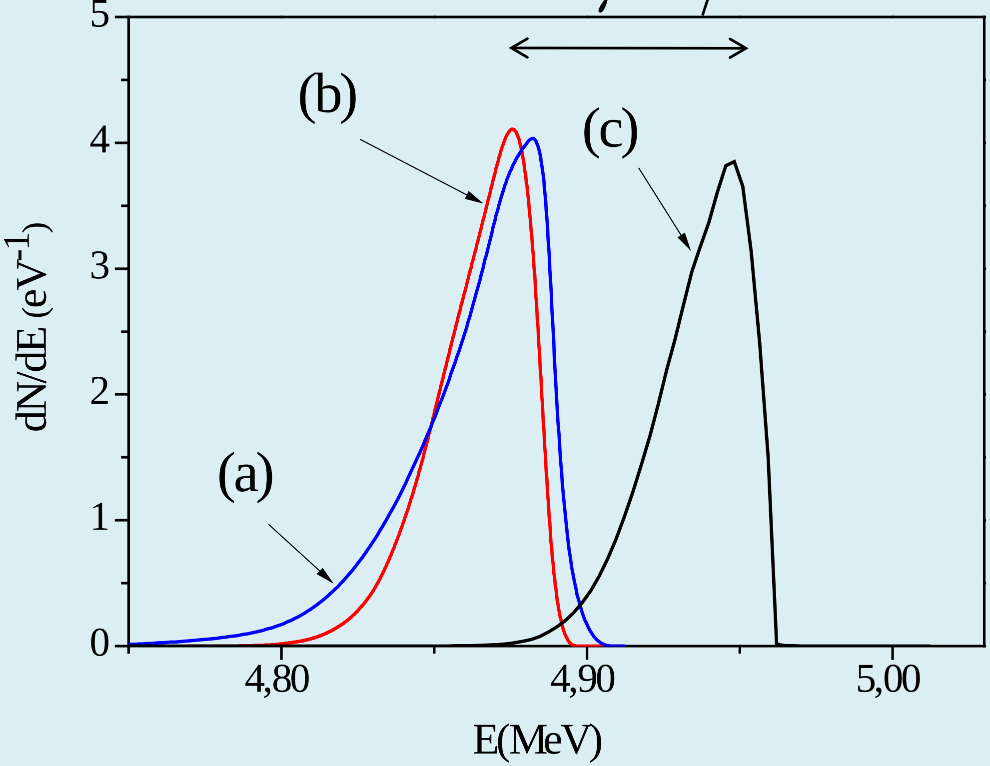
A new interaction chamber scheme 2/3

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



Quantum shift ΔE

$$\Delta = 4\gamma h\nu / mc^2$$



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

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