**Progetto SPARC e Proposta SPARX per un SASE FEL**

Luca Serafini  INFN-Milan e Universita’ degli Studi di Milano
On behalf of the SPARC Project Group

- **Genesis of a Program for an Italian Coherent X-ray Source**: *Fasella Panel & the PNR (National Research Plan)*

- **1st phase (R&D)**: the Project **SPARC** @ **LNF-INFN**

- **2nd phase**: the **F.I.R.B. Call for Proposals for a X-Ray laser SPARX (ENEA/CNR/INFN/Tor Vergata Univ.)** submitted
  aiming at building a **1.5 nm SASE-FEL**
Why a Coherent X-ray Source in Italy?

SASE-FELs will allow an unprecedented upgrade in Source Brilliance

Covering from the VUV to the 1 Å X-ray spectral range: new Research Frontiers

Intermediate between TTF-FEL (90-5 nm) and TESLA-FEL (1 Å)
X-ray sources over the last 100 years

**Average Brilliance [Phot. / (sec - mrad^2 - mm^2 - 0.1% bandwidth)]**

- 1st generation
- 2nd generation of synchrotron light sources
- 3rd generation

**Peak Brilliance [Phot. / (sec - mrad^2 - mm^2 - 0.1% bandwidth)]**

- X-ray tubes
- 2nd generation of synchrotron light sources
- 3rd generation

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What is a **SASE-FEL** Radiation Source?

a Bright Electron Beam propagating through an Undulator

**Spontaneous Radiation:**

peaked at \( \lambda_r \approx \lambda_u / 2\gamma^2(1 + K^2) \); \( \gamma \geq 2 \cdot 10^3 \)

**Beam rms divergence** \( \sigma' \approx 1/\gamma \approx 1 \cdot 100 \) \( \mu \)rad

*(Compton Backscattering of undulator virtual photons)*

\( I_r \approx N_e \); \( N_e \) number of electrons per bunch \( \approx 10^9 \)

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Interaction of $e^-$ with Spontaneous Radiation causes **Microbunching** and **SELF-AMPLIFICATION** of Spontaneous Emission (SASE)

In the **SASE mode** the Intensity:

\[ I_{ph} \approx N_e^\alpha \quad \alpha > 4/3 ; \quad N_e \text{ number of electrons} \approx 10^9 \]

**Amplification** gives extraordinary **High Photon Flux** (diffraction limited beam)

**Beam rms divergence** $\sigma' \approx \lambda / 2\pi\sigma_e \approx \text{few } \mu\text{rad}$

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• Brilliance (10 orders of magn. > 3rd generation SR sources)

• Transverse Coherence (diffraction limited) Pulse time structure < 100fs

• Spontaneous Radiation peaked at $\lambda_r \cong \lambda_u / 2\gamma^2(1 + K^2)$

$\lambda_u = 2$ cm $\gamma = 3 \cdot 10^4$ (15 GeV) $\lambda_r = 1$ Å, 12 keV
This Ultra-Bright Coherent Radiation opens up new Research Frontiers in several fields:

- Atomic physics
- Plasma and warm dense matter
- Femtosecond chemistry
- Life science
- Single Biological molecules and clusters
- Imaging / holography
- Micro and nano lithography

*X-rays are the ideal probe for determining the structure of matter on the atomic and molecular scale*

• Photon-cluster Interaction can cause:
  • Photo-fragmentation, Highly Charged Ions, Coulomb Explosion

• Direct Studies of FEL-Cluster Interaction
• Pump-probe Experiments using an external fs-laser
• For a focused beam all atoms in the Cluster could be ionized creating a ball of charge giving rise to a Coulomb Explosion (C.E.)
• C.E. Energies And Charge States are measured by observing the exploding fragments
• These effects will give insight into material damage induced by FEL Radiation
• **WATER WINDOW** (280-530 eV) is of extreme interest for **BIOLOGY**

• **CHROMOSOMES**

• **MALARIA INFECTED ERYTROCYTES**

• **CALCIFIED TISSUES**

• **MUSCLES**

• **LIPID MEMBRANES**

• **POLYMERS**
Protein Crystallography in Vivo with 100 fs X-Ray pulses

R. Neutze, R. Wouts, D. van der Spoul, E. Weckert, J. Hajdu;
Three Crucial Aspects drove the National Scientific Community and the Italian Department of Research (M.I.U.R.) to undertake a concrete initiative

• Funding Requirements and Man Power Requested
  100 M¤ ⇒ 500 M¤ initiative for Linac based SASE-FEL’s

• Strong and Wide Interdisciplinary Interest of National Research Institutes (ENEA, CNR, INFN, INFM)

• Existence of Two Major Proposals in the Intern. Scenario (LCLS @ SLAC & TESLA-FEL @ DESY) linked to serious R&D effort in the High Brightness Electron Beam Field
Wide International Community on High Brightness Beams

THE PHYSICS OF HIGH BRIGHTNESS BEAMS
Proc. of the 2nd ICFA Advanced Accelerator Workshop
University of California, Los Angeles, Nov. 1999
edited by James Rosenzweig & Luca Serafini

Web page: www.physics.ucla.edu/AABD

Physics and Science with the X-ray Free-Electron Laser
(Arcidosso, Italy, September 10-15, 2000)
C. Pellegrini and M. Cornacchia

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The Milestones

**1998 - The Fasella Panel**
A panel lead by **Paolo Fasella** (among other members, C. Rubbia and Björn Wiik) strongly encouraged the preparation of a proposal for the realisation in Italy of a *Ultra-high Brilliance X-ray Source*. The Panel gave serious recommendations to our Government for funding future initiatives in the field.

**2000 – PNR (National Research Plan)**
The Italian Government responded by allocating **96 M€** for a *Multi-purpose X-ray Laser with Ultra-High Brilliance* + **11 M€** for R&D activity focused on SASE-FEL’s driven by High Brightness Electron Beams, whose Call for proposals was published in February 2001 within a F.I.S.R. initiative.
The Project SPARC, based on a Collaboration CNR-ENEA-INFN-Tor Vergata Univ.-INFM-ST was approved in Feb. 2002 and funded in Jan. 2003

INFN: ultra-brilliant photoinjector at 150 MeV 4.4 M\(\text{\euro}\)
- Control the beam emittance and energy spread
- Compress the bunch-length by a factor $>5$ & test the RF compressor

ENEA: undulator for SASE-FEL @ 520-150 nm (green-UV) 3.2 M\(\text{\euro}\)
- Investigate the mechanism of High Order Harmonics generation

CNR: Optics for X-rays manipulation 1.3 M\(\text{\euro}\)

INFM: Soft X-ray Source 0.6 M\(\text{\euro}\)

Total funding = 9.5 M\(\text{\euro}\) (70% from MIUR, 30% from Institutions)
X-Ray FEL’s are based on SASE (no mirrors !) need Ultra-High Brightness e⁻ Beams

\[ \lambda_r = \frac{\lambda_u}{2\gamma^2} \left(1 + \frac{K^2}{2}\right) \]

Resonance Condition

\[ P_{FE\ell} = P_0 e^{2z/L_g} \]

- Self-Amplified-Spontaneous-Emission amplifies the spontaneous radiation exponentially in a single pass

- Interaction of a bright electron beam with noise in an undulator magnet results in a density modulation of the electron bunch at the optical wavelength: SASE instability leads to COHERENT EMISSION
Conditions for SASE

\[ \gamma = \text{norm. energy} \quad \varepsilon_n = \text{r.m.s. normalized emittance} \]
\[ I = \text{peak current} \quad \frac{\delta \gamma}{\gamma} = \text{energy spread} \]
\[ K = \text{undulator parameter} \propto \lambda_u B_u \]

A) Photon and Electron Beams must overlap in phase space

\[ \frac{\Delta \gamma}{\gamma} \leq \rho ; \quad \rho = \frac{\lambda_u}{4\pi\sqrt{3}L_g} \approx \begin{cases} 10^{-3} & @ 1 \text{ nm} \\ 5 \cdot 10^{-4} & @ 1 \text{ Å} \end{cases} \]

B) Cold Electron Beam (no damping of instability growth)

\[ L_g \propto \frac{\varepsilon_n \gamma^{3/2}}{I(1 + K^2/2)} \propto \frac{\gamma^{3/2}}{K\sqrt{B_n(1 + K^2/2)}} \]

R. Saldin et al. in Conceptual Design of a 500 GeV e+e- Linear Collider with Integrated X-ray Laser Facility, DESY-1997-048

\[ \lambda_r^{\text{MIN}} \propto \frac{\varepsilon_n}{K} \left( \frac{\delta \gamma}{\gamma} \right) \sqrt{\frac{1 + K^2/2}{I\gamma}} \propto \left( \frac{\delta \gamma}{\gamma} \right) \sqrt{\frac{1 + K^2/2}{\gamma B_n K^2}} \]

Brightness is what really matters!

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Transverse* Brightness of Electron Beams

\[
B_n = \frac{2I}{\varepsilon_{nx} \varepsilon_{ny}} \left[ \frac{A}{m^2 \text{rad}^2} \right]
\]

\( I = \text{peak current} \)

\( \varepsilon_{nx} = \text{rms normalized transverse emittance} \)

**Quality Factor**: beam peak current density normalized to the rms beam divergence angle

Round Beam: \( \varepsilon_{nx} = \varepsilon_{ny} \), \( J = I / \sigma^2 \) \( \Rightarrow \)

\[
B_n = \frac{2J}{(\sigma' \gamma)^2} = \frac{2J \sigma^2}{\varepsilon_n^2}
\]

* 5D Projection of 6D Brilliance used for Photon Beams

\[
B'_n = \frac{2I}{\varepsilon_{nx} \varepsilon_{ny}} \left[ \frac{eN_\gamma}{m^2 \text{rad}^2 \cdot \% \text{band}} \right]
\]

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Achieved Brightness in RF Photo-Injectors

\[
B_n \equiv \frac{2I}{\varepsilon_{nx}\varepsilon_{ny}} \left[ \frac{A}{m^2 \text{rad}^2} \right]
\]

\( I = \text{bunch peak current} \)

**TTF**  
photo-inj. (achieved)  \( 6 \cdot 10^{12} \)  
extit{exit of linac (compr.)}  \( 2 \cdot 10^{13} \)

**ATF**  
photo-inj. (achieved)  \( 5 \cdot 10^{13} \)  
@ photocathode  \( 1.2 \cdot 10^{15} \)

Max. achievable without compr.  \( \varepsilon_{n-cath} = \varepsilon_{thermal} \)

**LCLS** (requested @ 15 GeV)  \( 4 \cdot 10^{15} \)
\( \varepsilon_{nx} = \varepsilon_{ny} = 1.5 \ \mu m \)

**ESRF** (storage ring)  \( < 10^{14} \)
\( \varepsilon_{nx} = 20 \ \mu m \quad \varepsilon_{ny} = 0.07 \ \mu m \)

**SPARC** ultimate goal (Ph. 2)  \( 2 \cdot 10^{15} \)
**SPARC: 150 MeV Photo-injector R&D Project to investigate High Brightness e⁻ Beam Production**

**Frequency:** 2856 MHz

<table>
<thead>
<tr>
<th>GUN PARAMETERS</th>
<th>LINAC PARAMETERS</th>
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<tr>
<td>Peak Field: 120-140 MV/m (15 MW)</td>
<td>Accelerating Field: 25-30 MV/m (50 MW)</td>
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<td>Solenoid Field: 0.3 Tesla</td>
<td>Solenoid Field: 0.1 Tesla</td>
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<tr>
<td>Charge: 1 nC</td>
<td>Beam Energy: 150 MeV</td>
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<td>Laser: 10 ps x 1 mm (Flat Top)</td>
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SPARC Linac located in an existing underground Bunker
@ LNF

C. Sanelli
A view of the complex with Shielding Ground and building roof removed

C. Sanelli
The underground bunker as of early Oct. 2002

C. Sanelli
SPARC Building Complex
# SPARC Linac: the Time Table

<table>
<thead>
<tr>
<th>1.1 Laser</th>
<th>1.2 RF Gun</th>
<th>1.3 Linac</th>
<th>1.4 Diagn.-contr.</th>
<th>1.5 Commiss.</th>
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### SPARC é un progetto Speciale dell’INFN: Collaborazione LNF, Milano, Roma1, Roma2 (20 FTE)
State of the fundings MIUR for Photo-Injector

MIUR 3.057 k\(\text{\(\欧元\)}\)

INFN 2.818

Un. TV 92

ST 132

INFN Request of fundings:

- 2.310 k\(\text{\(\欧元\)}\) to complete Injector
- 700 k\(\text{\(\欧元\)}\) for group (3 yrs)
- 1.300 k\(\text{\(\欧元\)}\) for the velocity bunching

INFN 2.618 hardware
200 contracts

92 hardware
42 collabor.
• Collaborations and UE programs

BNL

UCLA

SLAC

SPARC

DESY

MOU

MOU

UE

UE

MOU
Innovative Concepts / Components in SPARC

- **Use of Shaped Laser Pulses** (minimize space charge non-linearities)

- **Implementation of Ferrario Working Point in an optimized integrated photo-injector** (proper phase tuning of emittance oscillations)

- **Applying Velocity Bunching with Emittance Preservation**
  (increasing peak current at no expense of transverse emittance)
Standard techniques (1)

Mapping of spectral domain into spatial domain

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Collinear Acousto-Optic modulator (AOM)

Propagation Delay

\[ \tau_g(\omega) = \frac{z(\omega)}{\nu_{g_1}(\omega)} + \frac{L-z(\omega)}{\nu_{g_2}(\omega)} \]
Numerical simulations for pulse shaping

- 100-fs input pulses at 800 nm
- Group delay and amplitude shaping
- 3rd harmonic with negligible pump depletion
- Ideal stretcher, amplifiers and compressor

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Numerical simulations (1)

\[ T_{\text{raise}} = 0.5 \text{ ps} \]
\[ T = 4 \text{ ps} \]

Transmission vs Wavelength (nm)

Group delay (ps) vs Wavelength (nm)
Magnetic field variation and rise time effects

No rise time
\[ \Delta B/B \approx 1\% \Rightarrow \text{Emitt. growth 20\%} \]

Rise time=1 psec
\[ \Delta B/B \approx 1\% \Rightarrow \text{Emitt. growth 60\%} \]
PRELIMINARY LAYOUT

\[ \begin{array}{cccc}
E=6.6 \text{ MeV} & E=20 \text{ MeV} & E=45 \text{ MeV} & E=122 \text{ MeV} \\
RF \text{ gun} & \text{TW linac} & \text{TW linac} & \text{TW linac} \\
& B=1150 \text{ gauss} & B=1480 \text{ gauss} & B=1440 \text{ gauss}
\end{array} \]

\[ \text{I}_{\text{peak}}=500 \text{ A} \]
\[ \text{E}_n=0.6 \pi \text{ mm mrad} \]
\[ \Delta \text{E}/\text{E}=\pm 2.25\% \]

First PARMELA Simulation of RF Compressor

C. Ronsivalle

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Velocity-Ballistic bunching observed

- Compression better than chicane (<0.4 ps)
  - Linearity of the rf used to focus gives smaller long. emittance
  - At resolution limit of interferometer
- What are the effects on transverse phase space?

J. Rosenzweig, UCLA
RF Compression at DUVFEL
(B. Graves & Ph. Piot)

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The Italian Program for a SASE X-ray FEL

• Call for proposals published by the Italian Government in December 2001

• 96 M$ allocated for an Ultra-brilliant multi-purpose pulsed X-Ray Laser

• SPARX proposal submitted in Feb. 2002 by a collaboration CNR-ENEA-INFN-Rome Univ. “Tor Vergata”

• FERMI@ELETTRA by INFM & Sincrotrone Trieste

$ only National Research Institutions were eligible to apply
A Set of Parameters
1) Consistent with the available budget
2) Evolutionary toward 1 Å ($\approx 10$ GeV)

- 2.5 GeV is consistent with $\lambda = 1.5$ nm

- $\lambda$ [Å] 15 $\Rightarrow$ 1 Å
- $I$ [kA] 2.5 $\Rightarrow$ 3-5
- $\varepsilon_n$ [$\mu$m] 2 (1 slice) $\Rightarrow$ $\approx 1$
- $\Delta\gamma/\gamma$ [%] $\leq 0.1$ $\Rightarrow$ $\approx 0.07$

As indicated by the Presidents of the collaborating Institutions, the project should be evolutionary, i.e. compatible to a long term upgrade aiming at the final goal of a 1 Å Coherent Radiation Source.
Examined two solutions: S-band normal conducting and L-band SC

S-band Room-Temperature

150 MeV 1 GeV 2.5 GeV
700 A 700 A 2.5 kA

S-band Photoinector with RF Compressor
RF Gun + 4 SLAC TW

SLAC TW Acc. Structures

Magnetic Compressor

SLAC TW Acc. Structures

$E_{\text{acc}} = 18-20 \text{ MeV/m}$

200 m
3D simulation with GENESIS @ 1.5 nm

Tab. 3: Undulators characteristics

<table>
<thead>
<tr>
<th></th>
<th>Undulator 1 @1.5 nm</th>
<th>Undulator 2 @13.5 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Hahlo</td>
<td>Hahlo</td>
</tr>
<tr>
<td>Period</td>
<td>3 cm</td>
<td>5 cm</td>
</tr>
<tr>
<td>K</td>
<td>1.67</td>
<td>4.88</td>
</tr>
<tr>
<td>Gap</td>
<td>12.67 mm</td>
<td>12.16 mm</td>
</tr>
<tr>
<td>Residual Field</td>
<td>1.25 T</td>
<td>1.25 T</td>
</tr>
</tbody>
</table>

Tab. 4: FEL-SASE expected performances

<table>
<thead>
<tr>
<th>Wavelength (λ)</th>
<th>1.5 nm</th>
<th>13.5 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation length</td>
<td>24.5 m</td>
<td>14.5 m</td>
</tr>
<tr>
<td>Peak Power</td>
<td>10^{10} W</td>
<td>4 \times 10^{10} W</td>
</tr>
<tr>
<td>Peak Power 3 harm.</td>
<td>2 \times 10^8 W</td>
<td>5 \times 10^9 W</td>
</tr>
<tr>
<td>Peak Power 5 harm.</td>
<td>3 \times 10^7 W</td>
<td>2 \times 10^8 W</td>
</tr>
<tr>
<td>Brilliance</td>
<td>1.8 \times 10^{31}</td>
<td>2 \times 10^{32}</td>
</tr>
<tr>
<td>Brilliance 3 harm.</td>
<td>10^{29}</td>
<td>10^{31}</td>
</tr>
<tr>
<td>Brilliance 5 harm.</td>
<td>9 \times 10^{28}</td>
<td>3 \times 10^{29}</td>
</tr>
</tbody>
</table>

rms spot size 50 µm
rms divergence 5 µrad
Cost of a 1.5 nm source

Costs (in M\(\text{\$}\)) are expected to be restricted to

<table>
<thead>
<tr>
<th>Component</th>
<th>Cost (M(\text{$}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac</td>
<td>34</td>
</tr>
<tr>
<td>Undulators</td>
<td>10</td>
</tr>
<tr>
<td>Radiation beam lines</td>
<td>10</td>
</tr>
<tr>
<td>Contingency</td>
<td>13</td>
</tr>
</tbody>
</table>

Linac’s Cost Estimates are:

- **L-band Linac** (Tesla type) 40 (injector included)
- **S-band Linac** (Slac type) 32 (injector included)

Infrastructures: 12.5 M\(\text{\$}\) (external funding)
High Brightness electron beams are crucial for many Applications

\[ L_g \propto \frac{\gamma^{3/2}}{K \sqrt{B_n (1 + K^2 / 2)}} \]

SASE FEL's

\[ \varepsilon_n \leq \sqrt{\gamma \frac{\Delta n_p \lambda_p}{n_p 2\pi}} \]

Plasma Accelerators

\[ N_X \propto \sum T f \frac{N e - N_h \nu}{\varepsilon_n \beta^*} \gamma ; \beta^* > \sigma_z \]

Relativistic Thomson Monochromatic X-Ray Sources

\[ \Phi_p \approx 50 \mu m \]
\[ \lambda_p \approx 30 - 100 \mu m \]

Fig. 2 Thomson scattering geometry

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